



Modelling of Integrated Systems and Systems Analysis

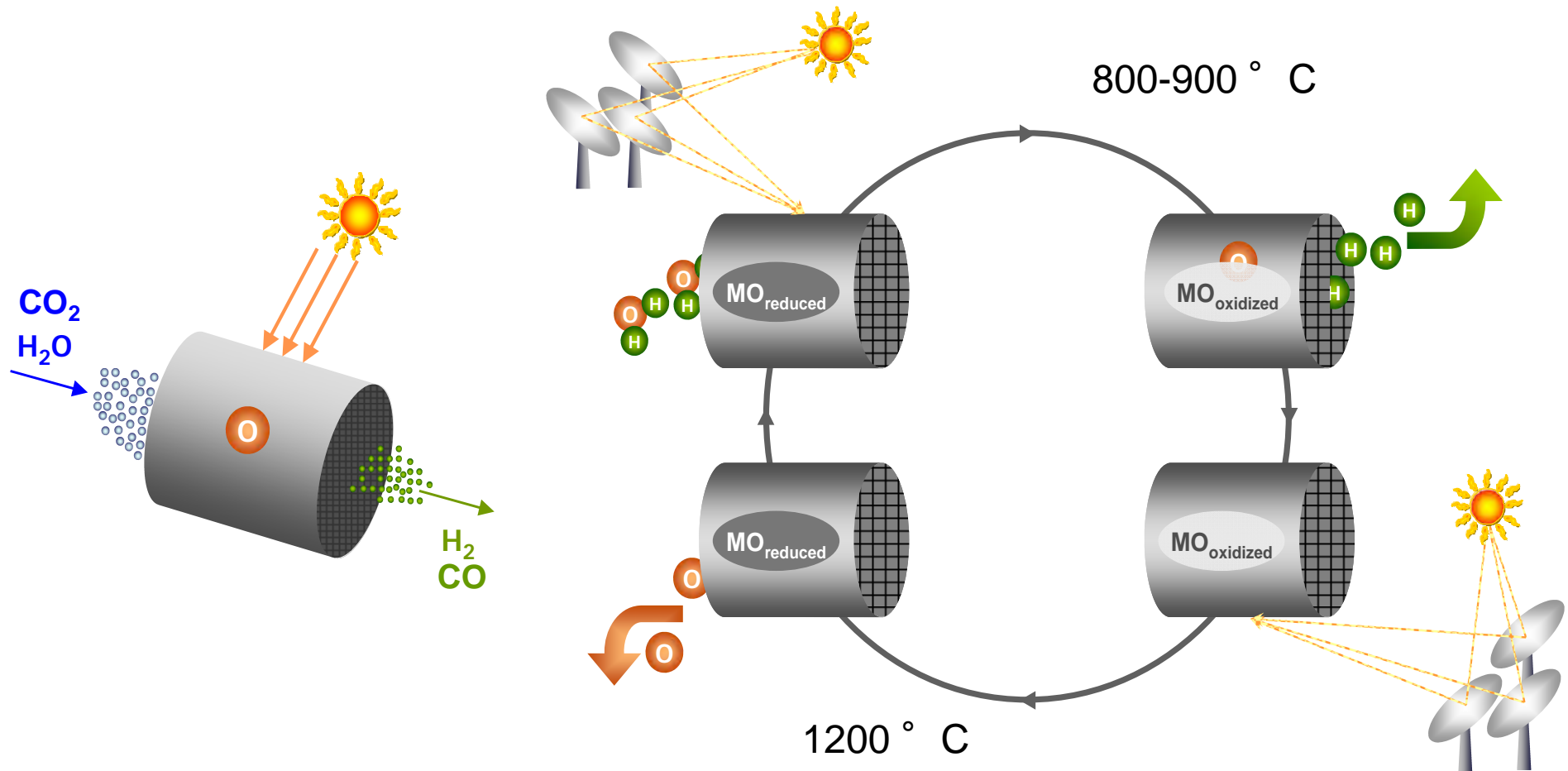
C. Sattler, F. Trieb, A. Houaijia, S. Breuer, M. Roeb



Outline

- Examples
 - Hydrosol
 - Process and History
 - Process modelling
 - Exergy analysis
 - Receiver-Reactor Optimization
 - HyCycleS
 - Scale-up
 - Economic Evaluation
 - SOLREF
 - Systems analysis
- Summary and Outlook

Fuel Production from H_2O and CO_2 by Solar Radiation

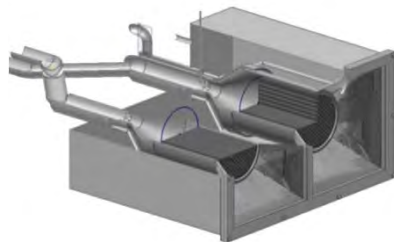
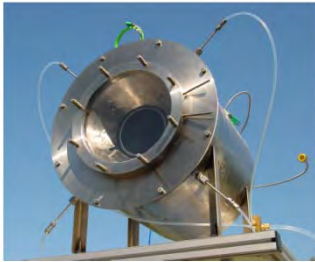


DLR: Roeb, Müller-Steinhagen, *Science*, Aug. 2010



HYDROSOL History

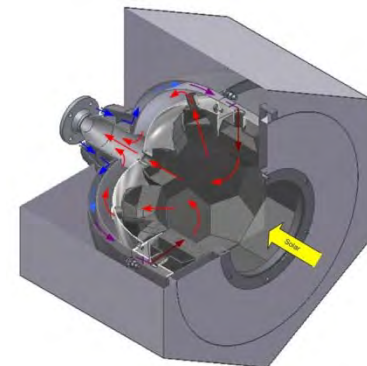
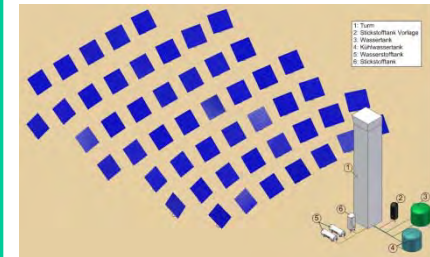
Hydrosol I
2002 – 2005
10 kW



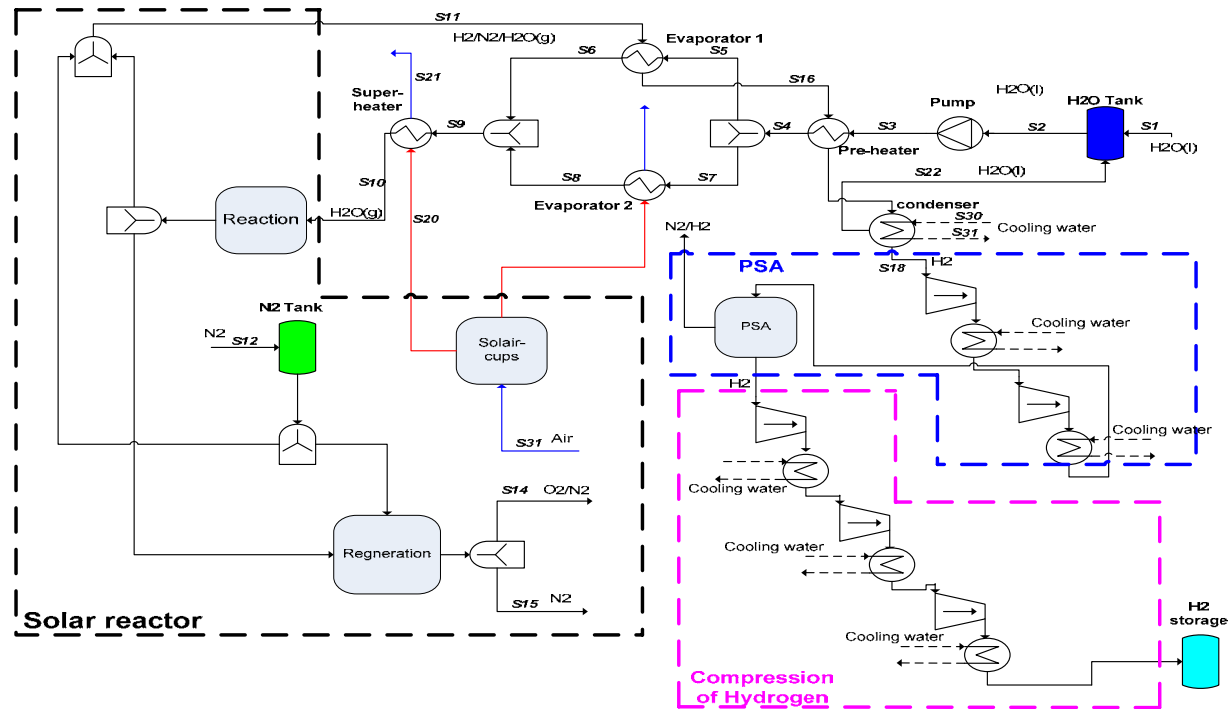
Hydrosol II
2006 – 2009
100 kW



Hydrosol 3D
2010 – 2012
1 MW



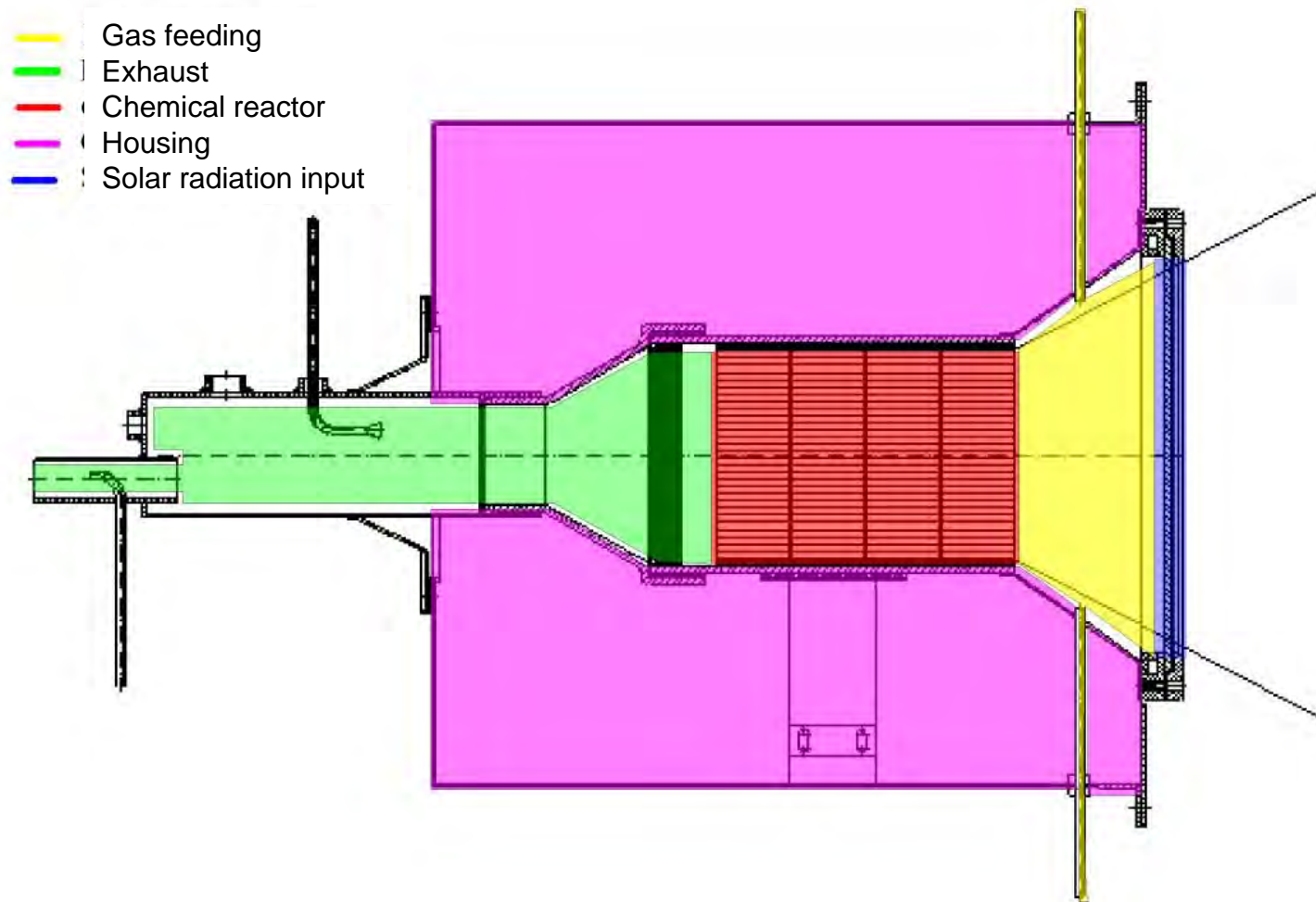
Steady state simulation of the process



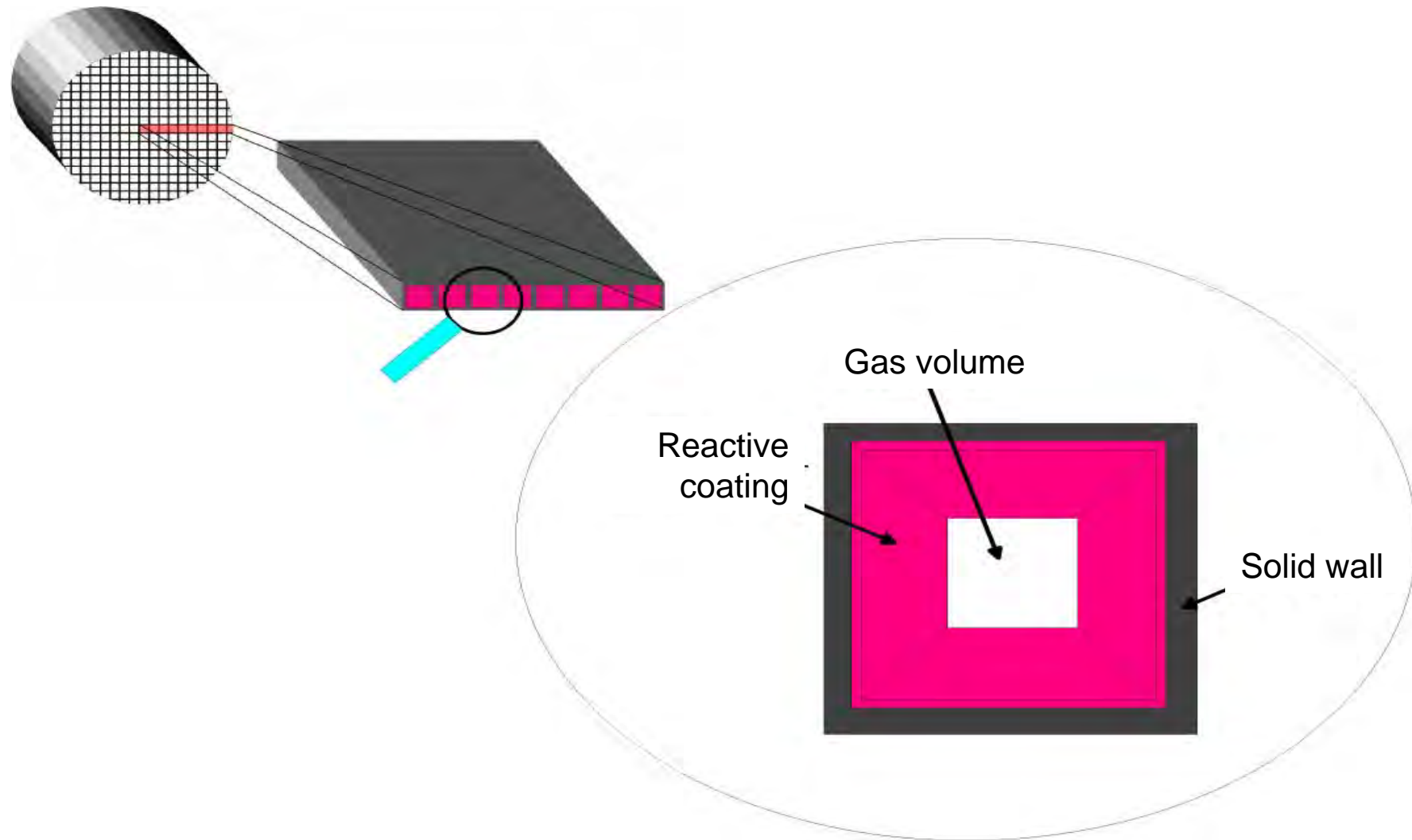
Operation	Component ID in Flow Sheet	Heat duty kW]
Water preheating	Pre-heater	9.75
Water evaporation of sub-stream 1	Evaporator 1	61.78
Water evaporation of sub-stream 2	Evaporator 2	91
Water superheating	Super-heater	12.84
Reactor		
<i>Hot air generation</i>	Solar cups	131
<i>Reaction step</i>	Reaction	350
<i>Regeneration step</i>	Regeneration	500



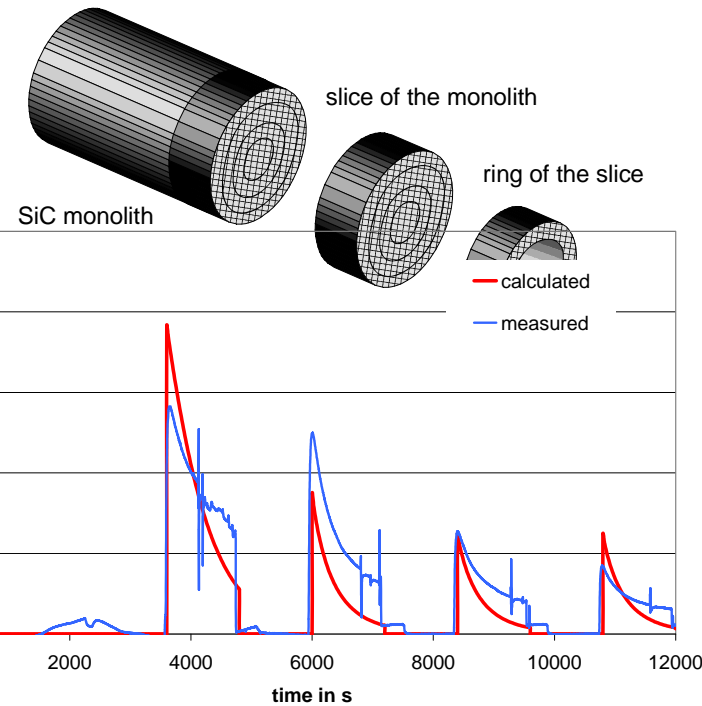
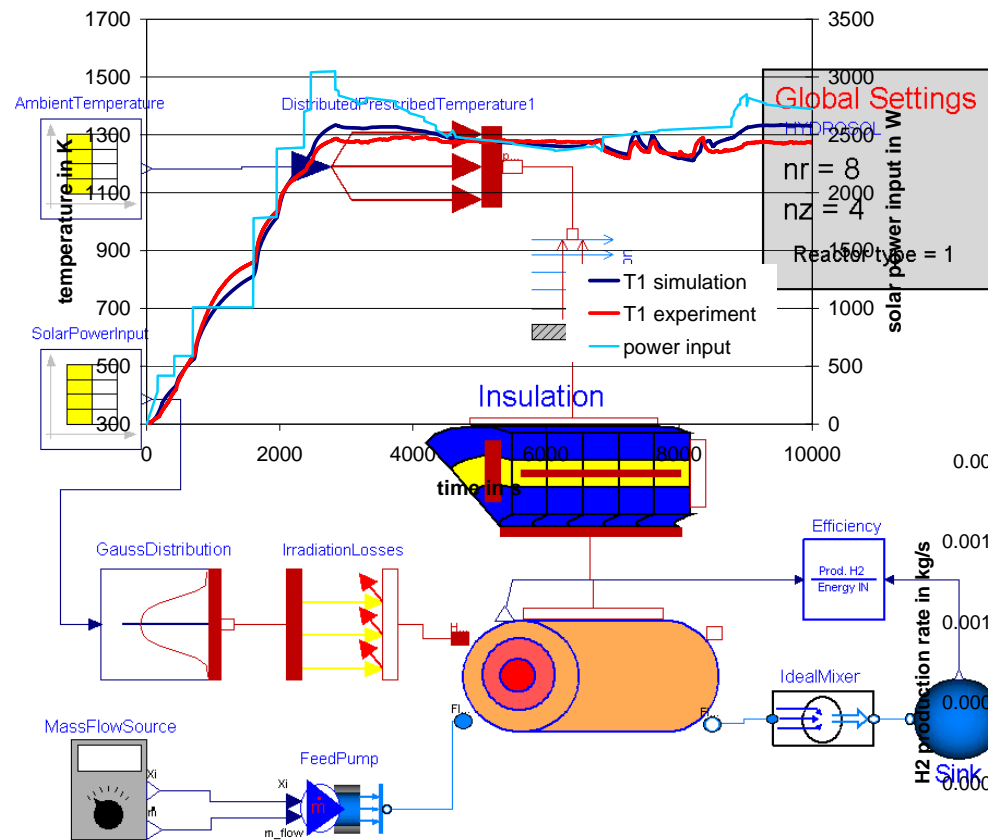
Modelling of the transient behaviour of the reactor



Submodel of the Reactor



Model for the receiver-reactor



Exergy analysis

- Exergetic efficiency of a component: $\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}}$
- Exergy destruction ratio in a component: $\varepsilon_k = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}}$
- Overall system exergetic efficiency: $\varepsilon_{tot} = \frac{\dot{E}_{P,tot}}{\dot{E}_{F,tot}}$



Exergy analysis

Process unit	E_F [kW]	E_P [kW]	E_D [kW]	ε_K [%]	y_k [%]
Solar reactor	896	283,05	612,95	31,59	60,51
Pre-heater	3,26	1,26	2	38,65	0,19
Evaporator 1	35,89	14,02	21,87	39,06	2,15
Evaporator 2	41,03	20,59	20,44	50,18	2,01
Super-heater	4,69	3,97	0,7	84,64	0,0001
PSA	16,049	3,84	12	23,92	1,18
Hydrogen compression	16,04	7,06	8,98	44,01	0,88
Overall system	1012,95	333,79	679,16	32,95	

The optimization of the solar reactor and the evaporators is required due to the high exergy destruction ratio.



Design criteria for the receiver-reactor

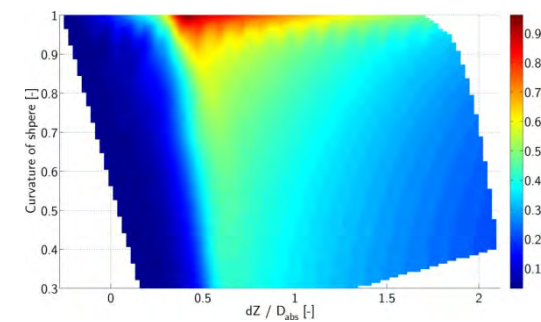
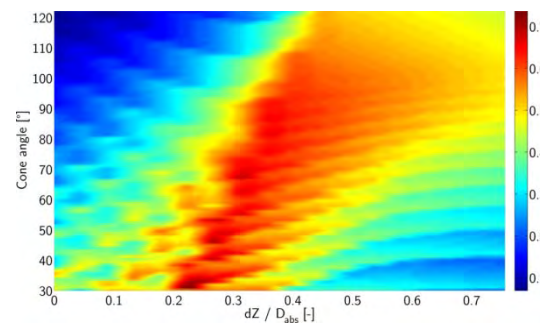
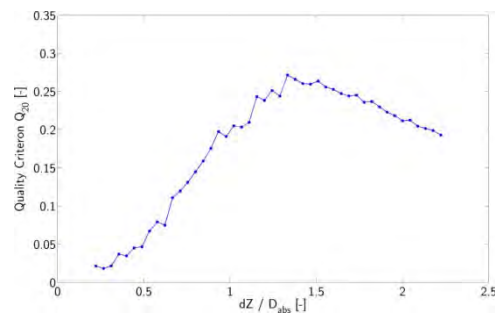
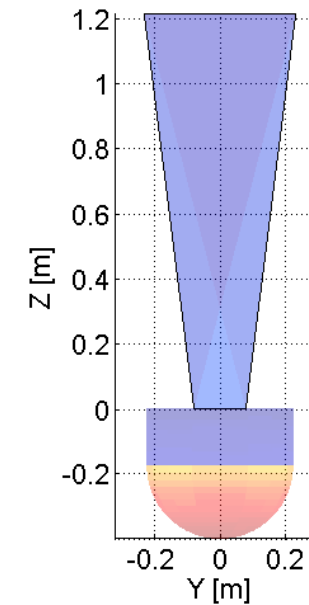
- Minimizing of aperture
- Maximizing of absorber volume
- Homogeneous flux and temperature distribution
- Easy maintainance and straightforward replacement of absorber modules

→ Cavity design with secondary concentrator

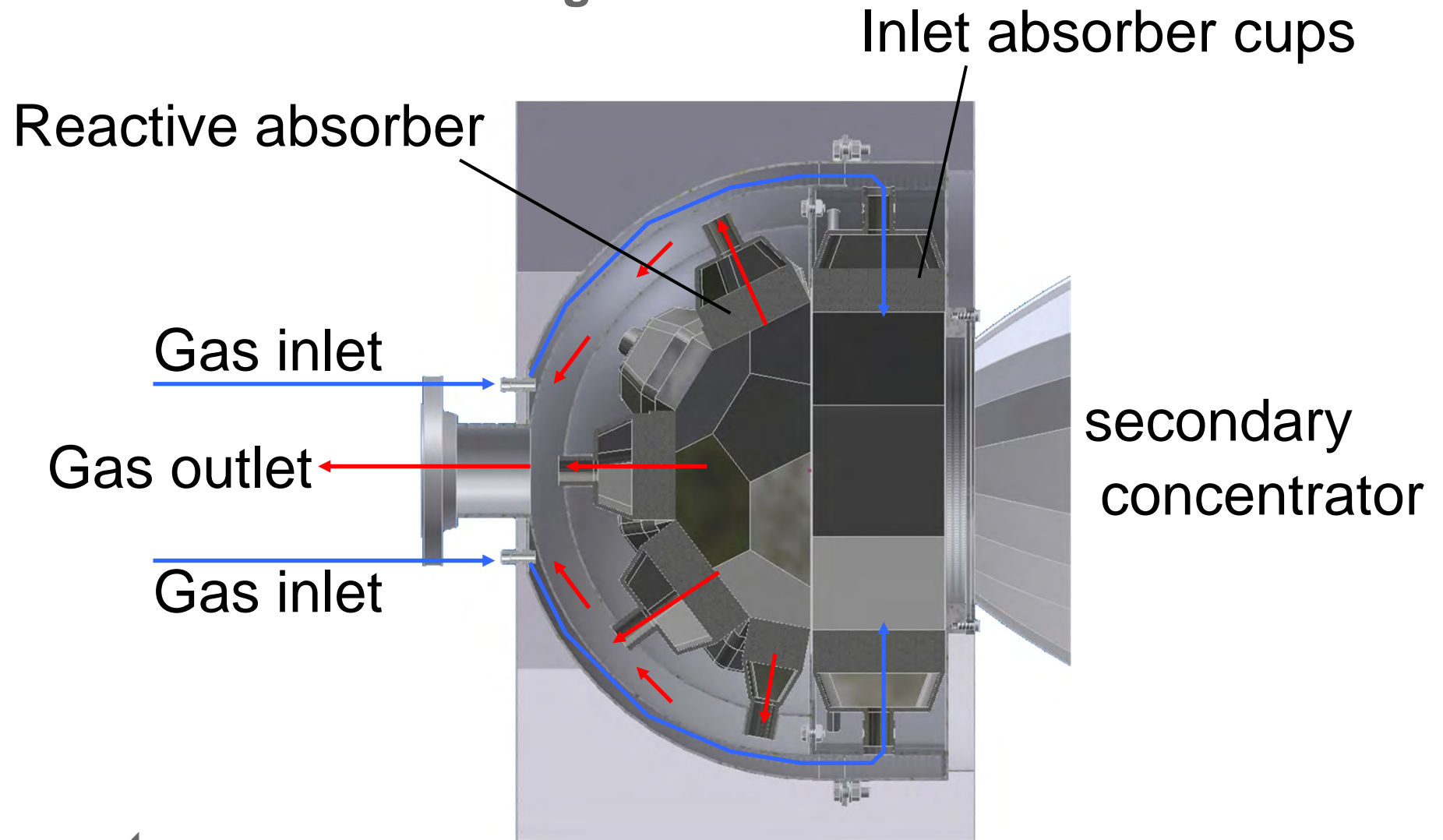


Results of Absorber Shape Variation

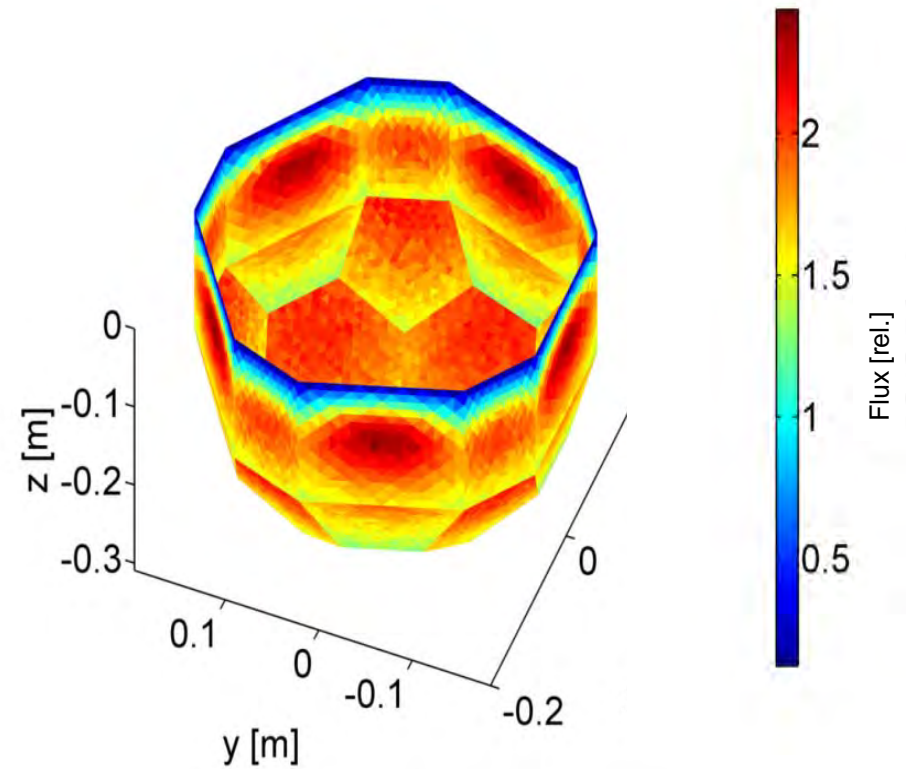
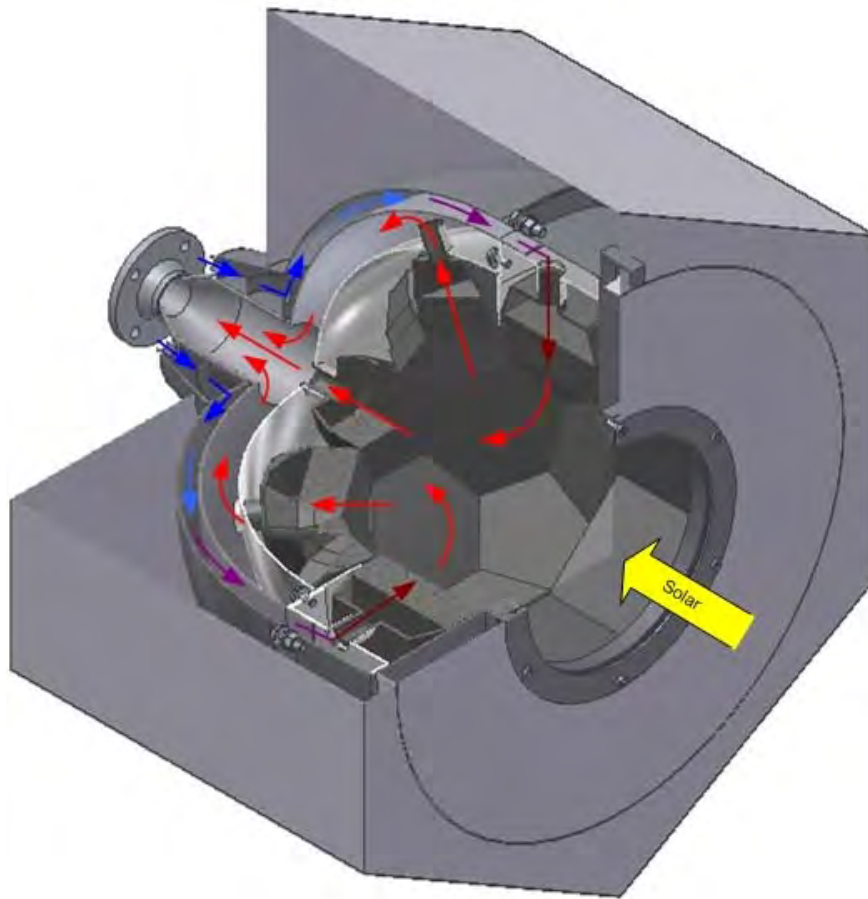
Absorber shape	Max. Quality value [-]
Flat	0,26
Conical	0,72
Spherical	0,94



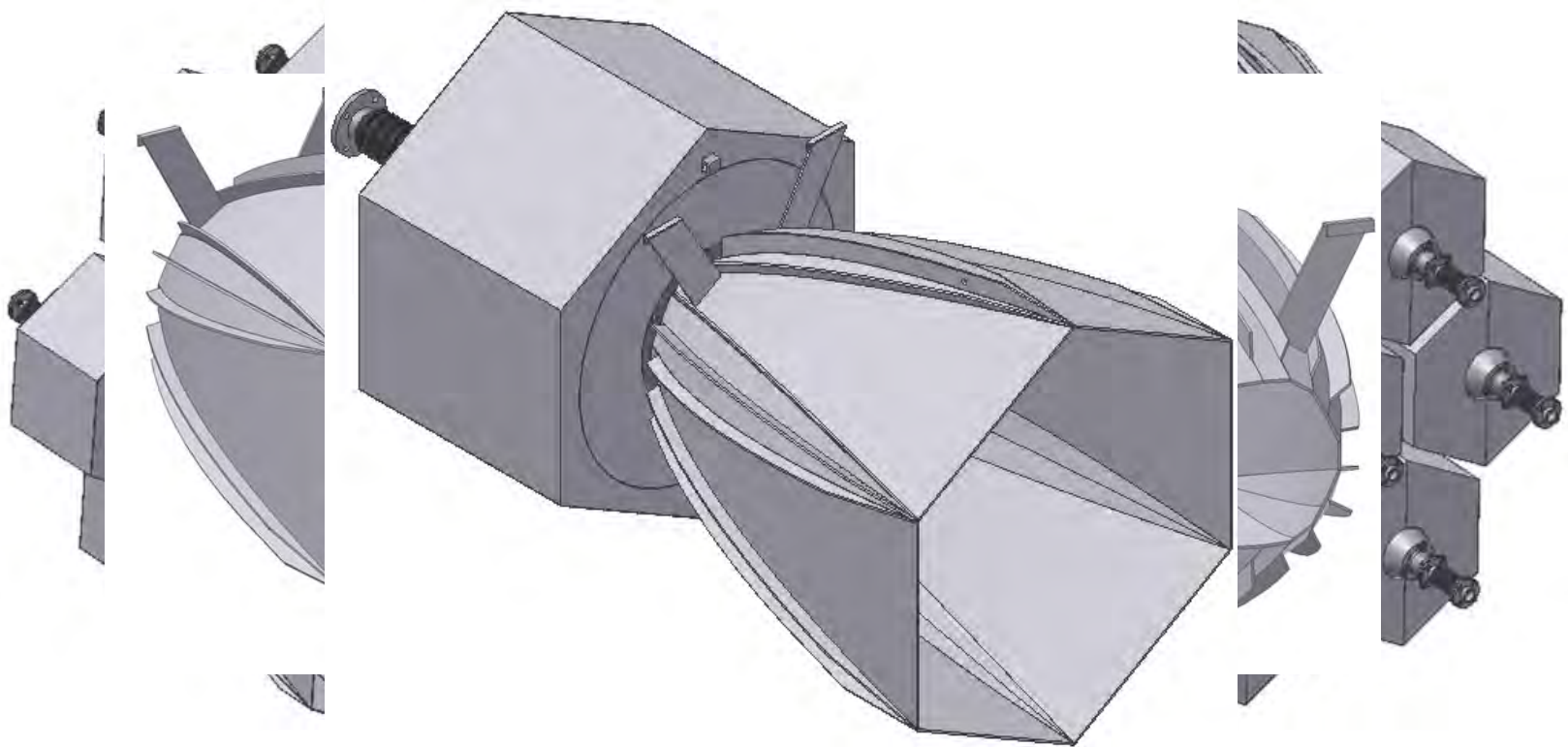
New Receiver Design



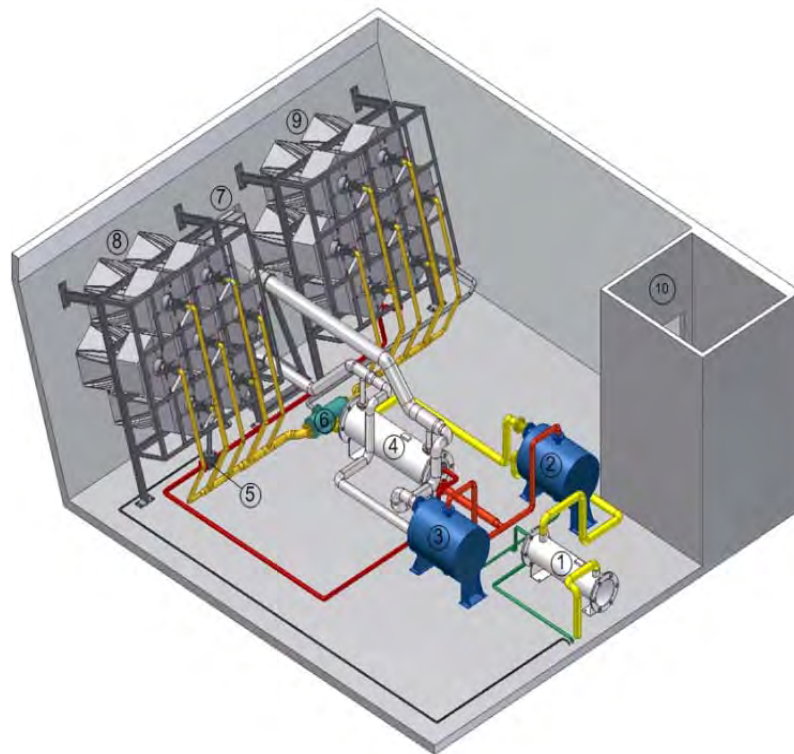
Working Principle of Reactor



Reactor Optimisation and Set-up



Integration of the HYDROSOL plant into a solar tower

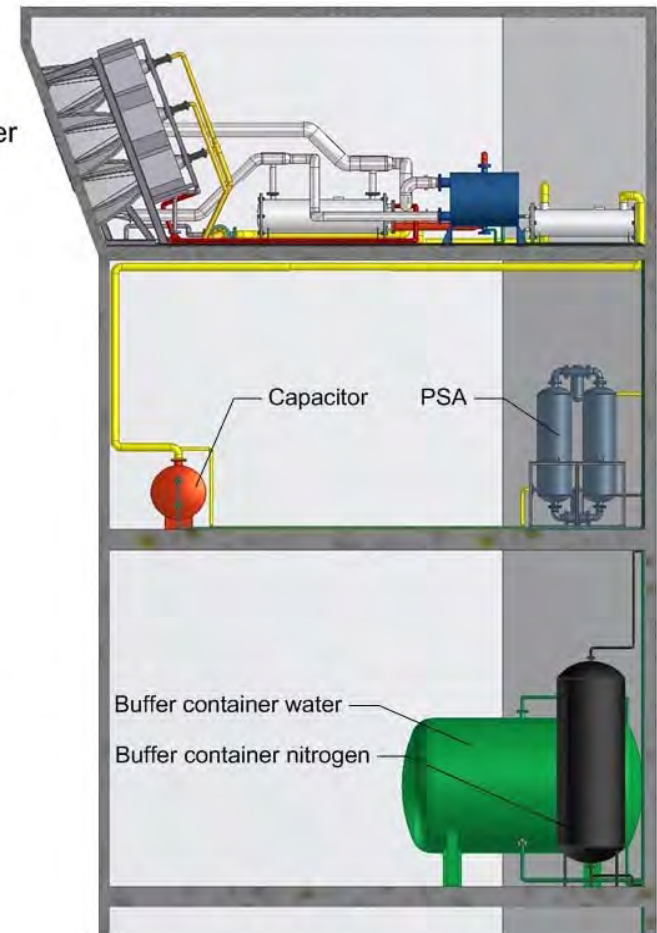


- 1: Preheater
- 2: Vaporizer 1
- 3: Vaporizer 2
- 4: Superheater
- 5: Way Valve 1
- 6: Way Valve 2
- 7: Air Receiver
- 8: Reactor Group 1
- 9: Reactor group 2
- 10: Elevator

Reactor chamber

Outlet level

Buffer level

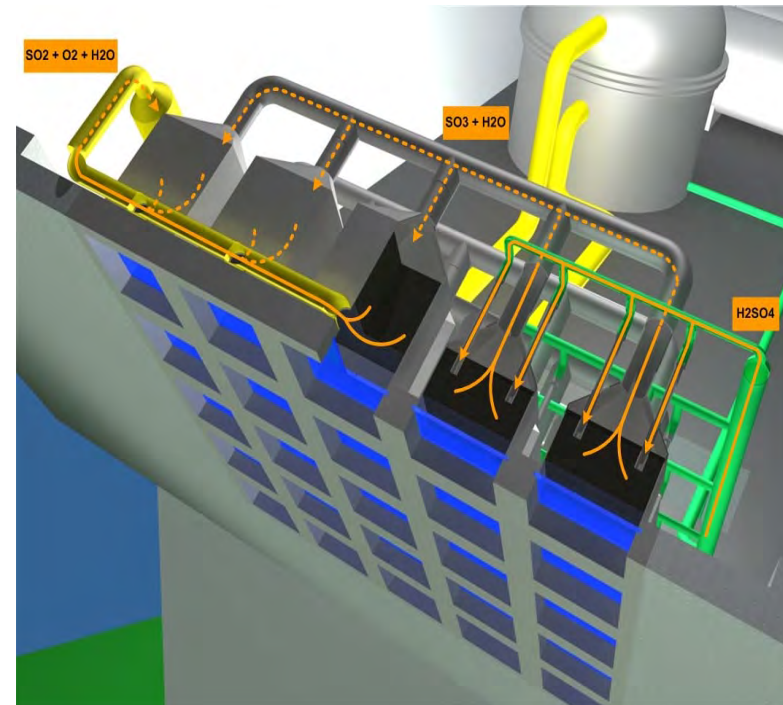
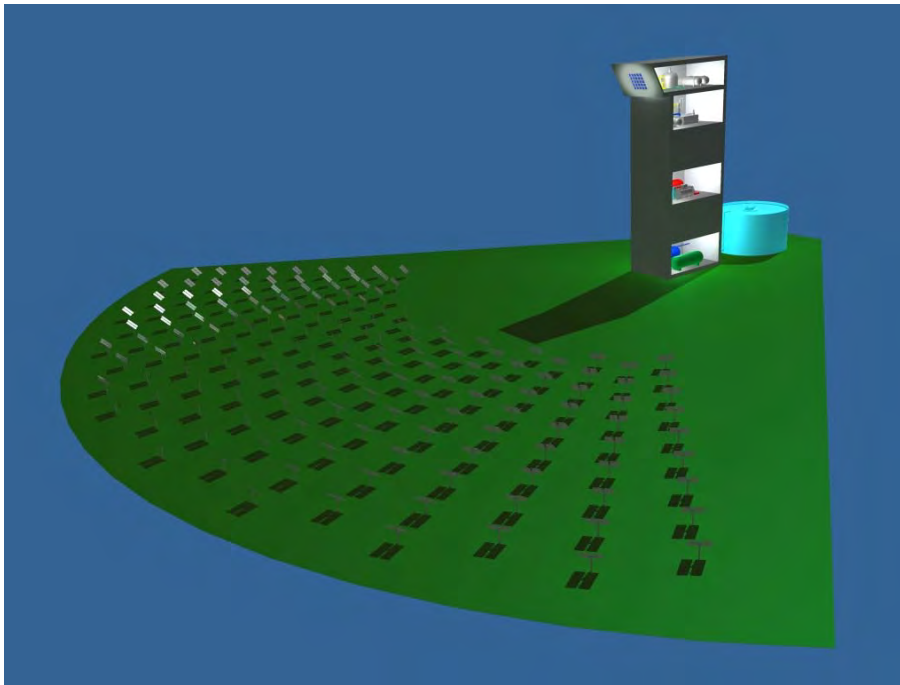


Buffer container water

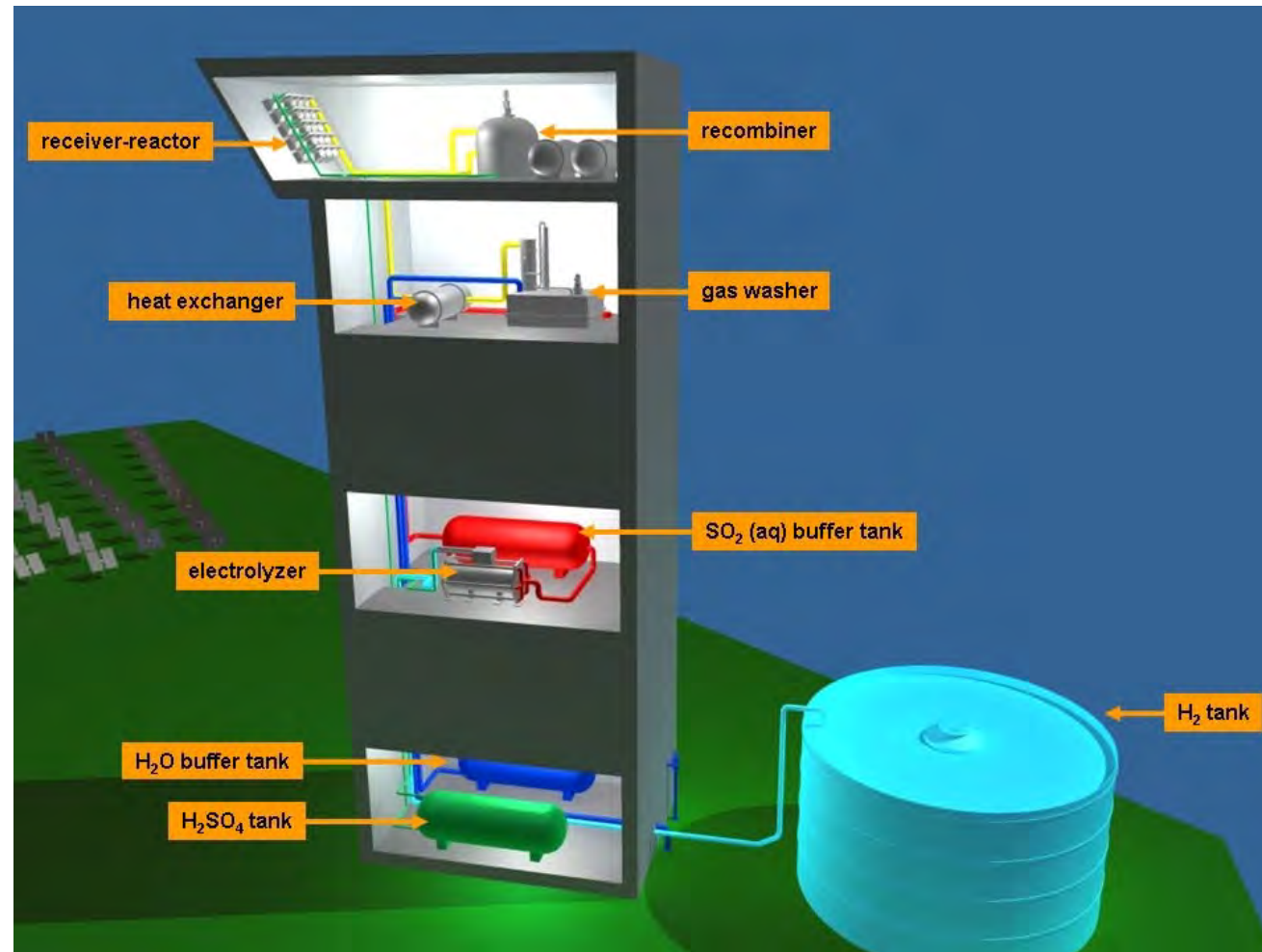
Buffer container nitrogen



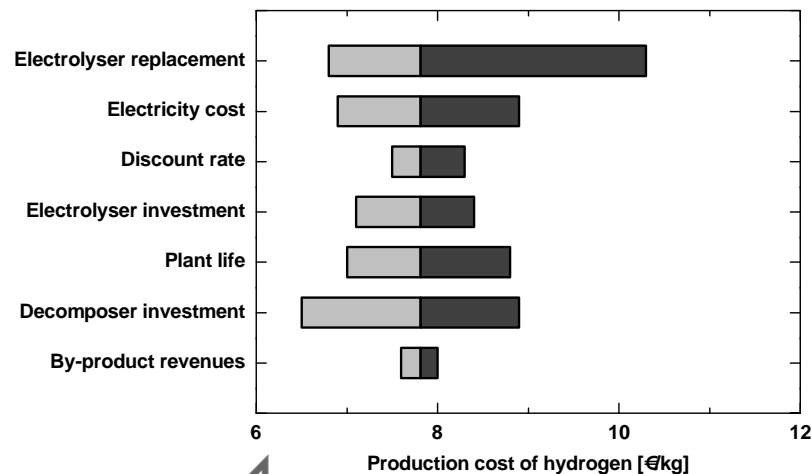
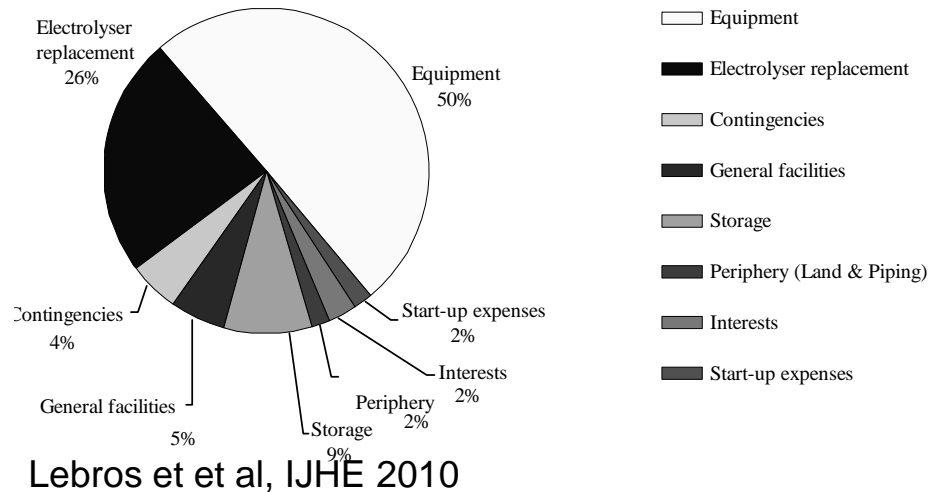
Scale-up of the solar HyS process



Implementation into a Solar Tower



Techno-economics

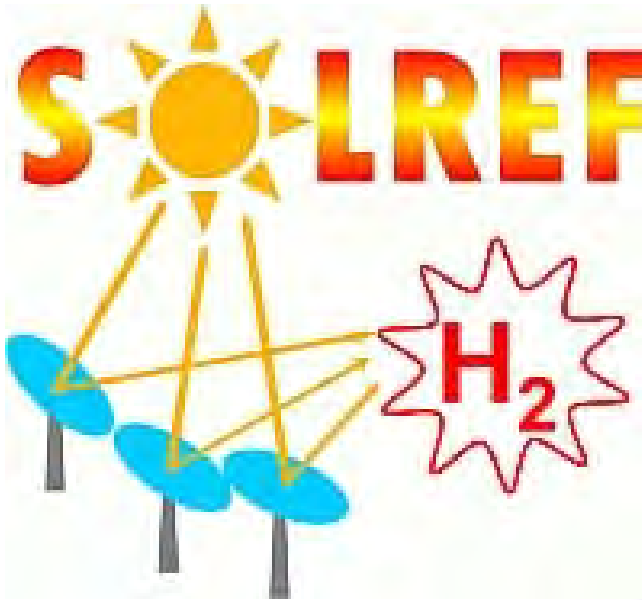


- Flowsheet for solar HyS process refined and completed
- All Components including the solar field were sized for a nuclear HyS and SI process and a solar HyS process
- Investment, O&M cost, production cost were analysed
→ 6-7 €/kg(H₂) for HyS
→ optimistic scenarios lead to 3.5 €/kg(H₂)
- 50 MW solar tower plant for hydrogen production by HyS cycle defined and depicted
- Thorough safety analysis was carried out for respective nuclear and solar power plants





Systems Analysis – Market Study

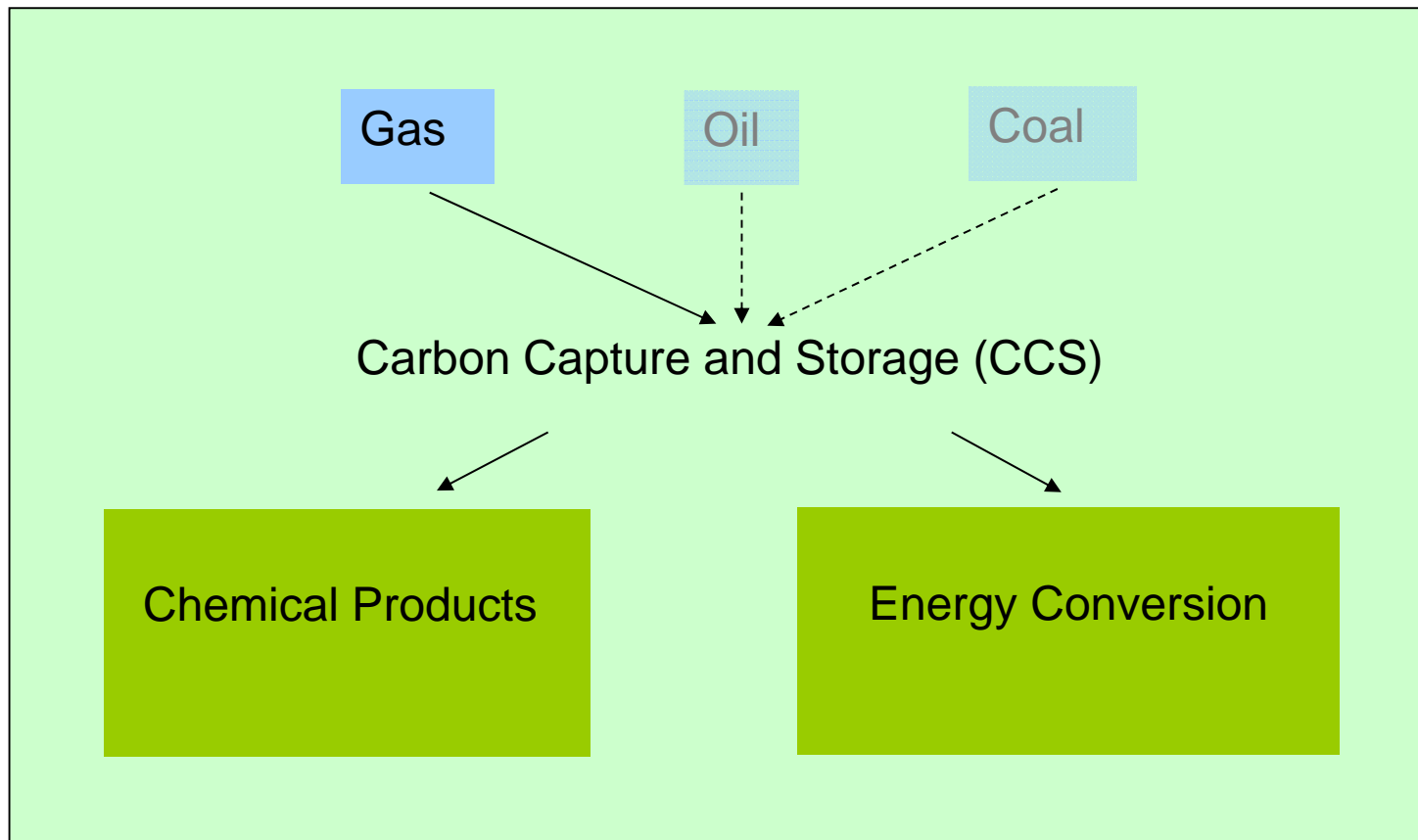


Systems Analysis - Market Study

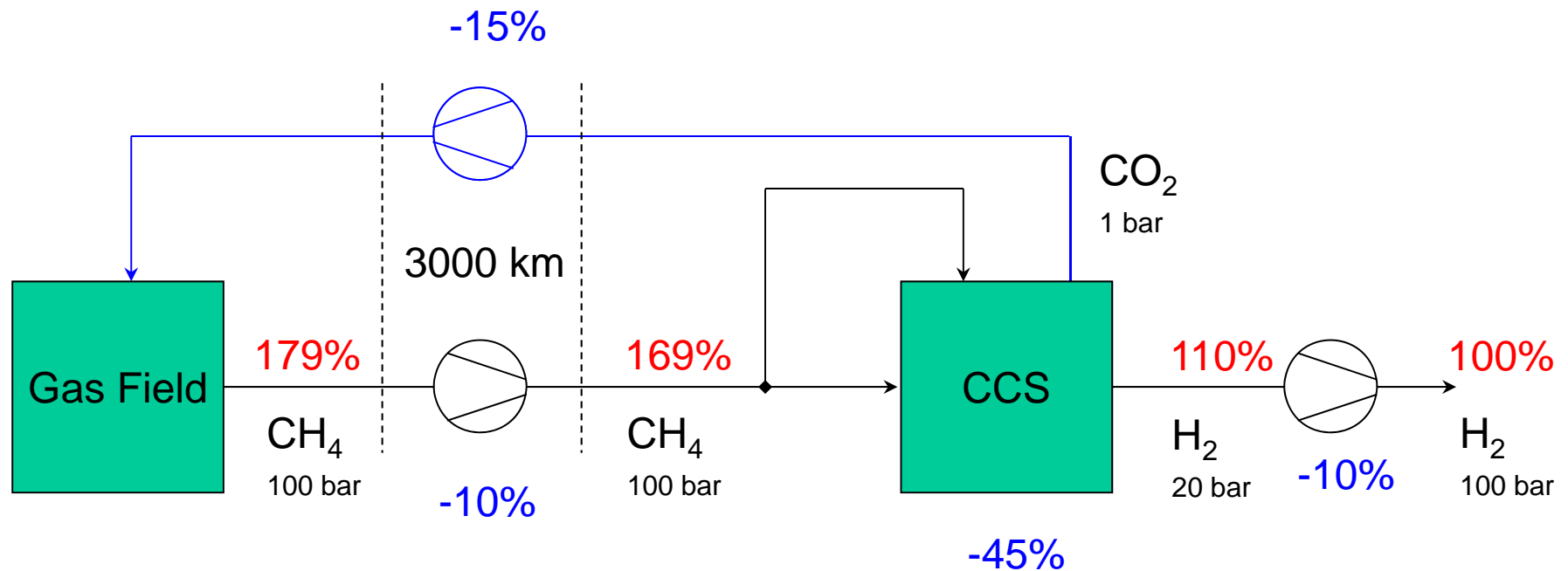
- Market Niches
- Resource Potentials
- Market Scenarios
- Environmental Impacts
- Socio-Economic Impacts



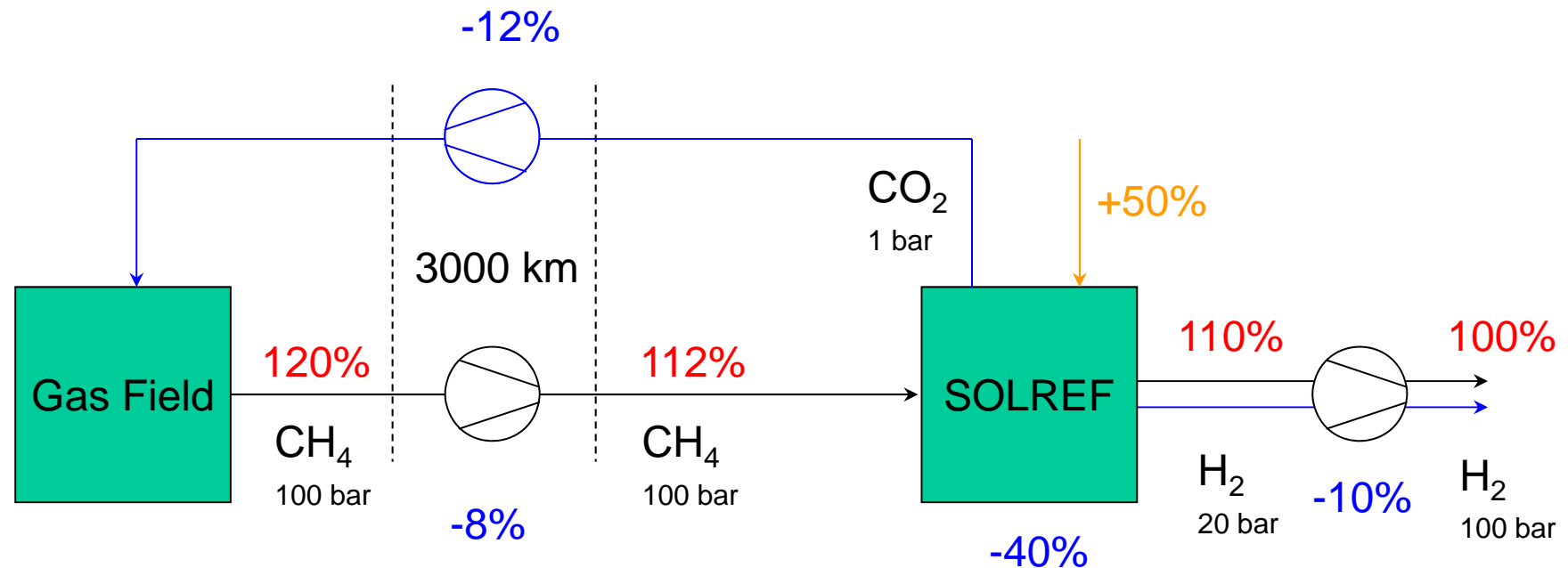
Market Niches for Solar Syngas/H₂



Case 1: Conventional CCS at Consumer and Transport of CO₂ to Gas Field



Case 2: Solar CCS at Consumer and Transport of CO₂ to Gas Field



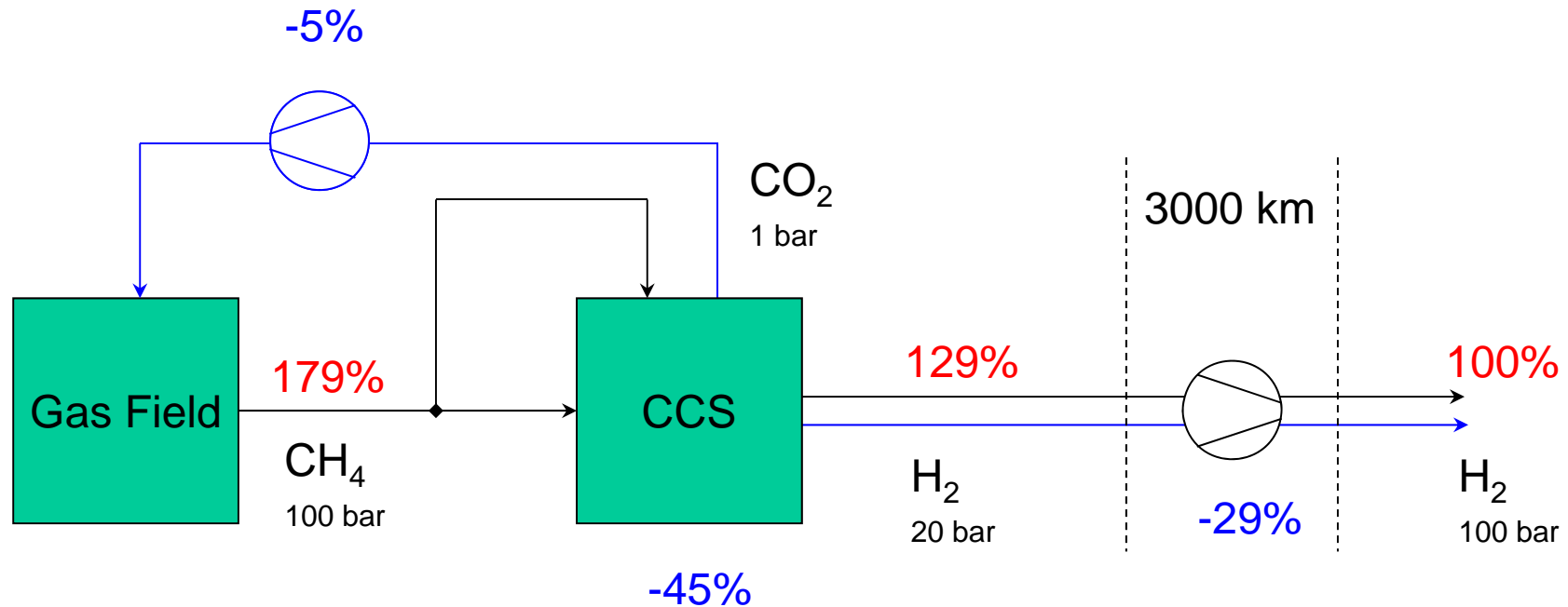
Energy Content
in Units of
Product Gas

Energy Losses
in Units of
Product Gas

Solar Energy
Input in Units
of Product Gas



Case 3: Conventional CCS at Source and Transport of H₂ to Consumer



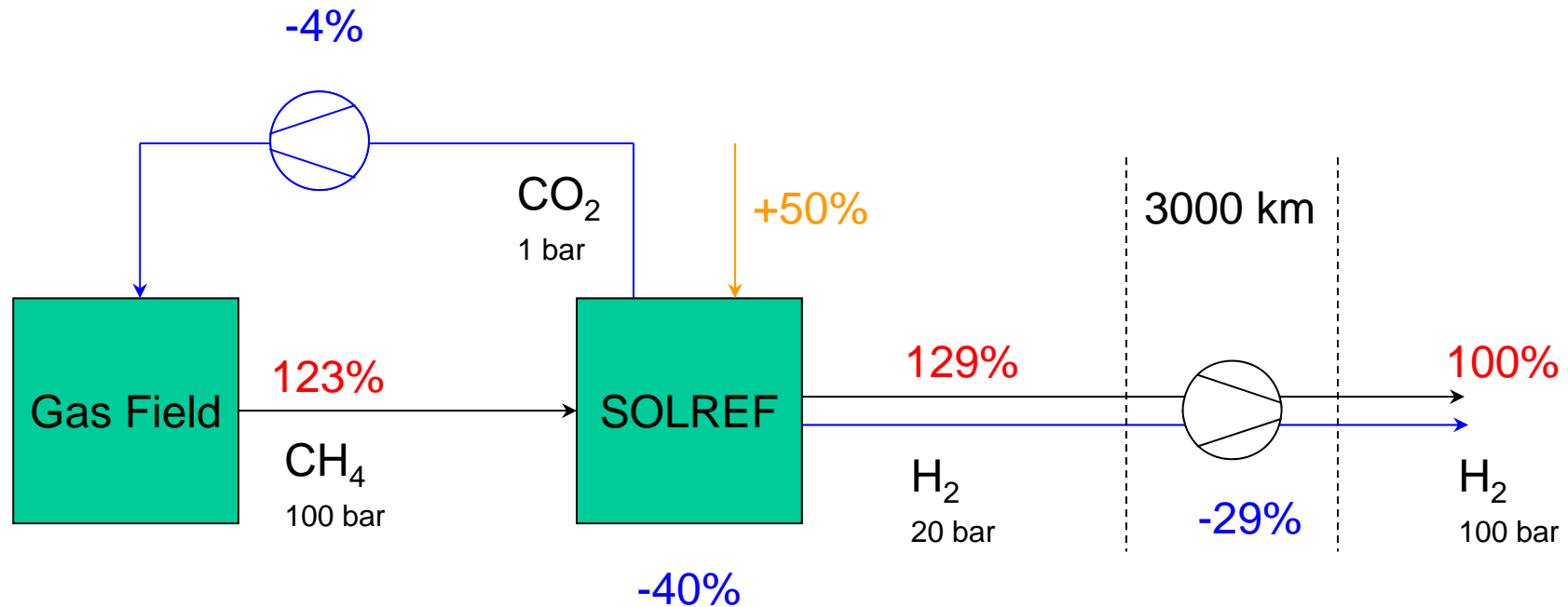
Energy Content
in Units of
Product Gas

Energy Losses
in Units of
Product Gas

Solar Energy
Input in Units
of Product Gas



Case 4: Solar CCS at Source and Transport of H₂ to Consumer



Energy Content
in Units of
Product Gas

Energy Losses
in Units of
Product Gas

Solar Energy
Input in Units
of Product Gas

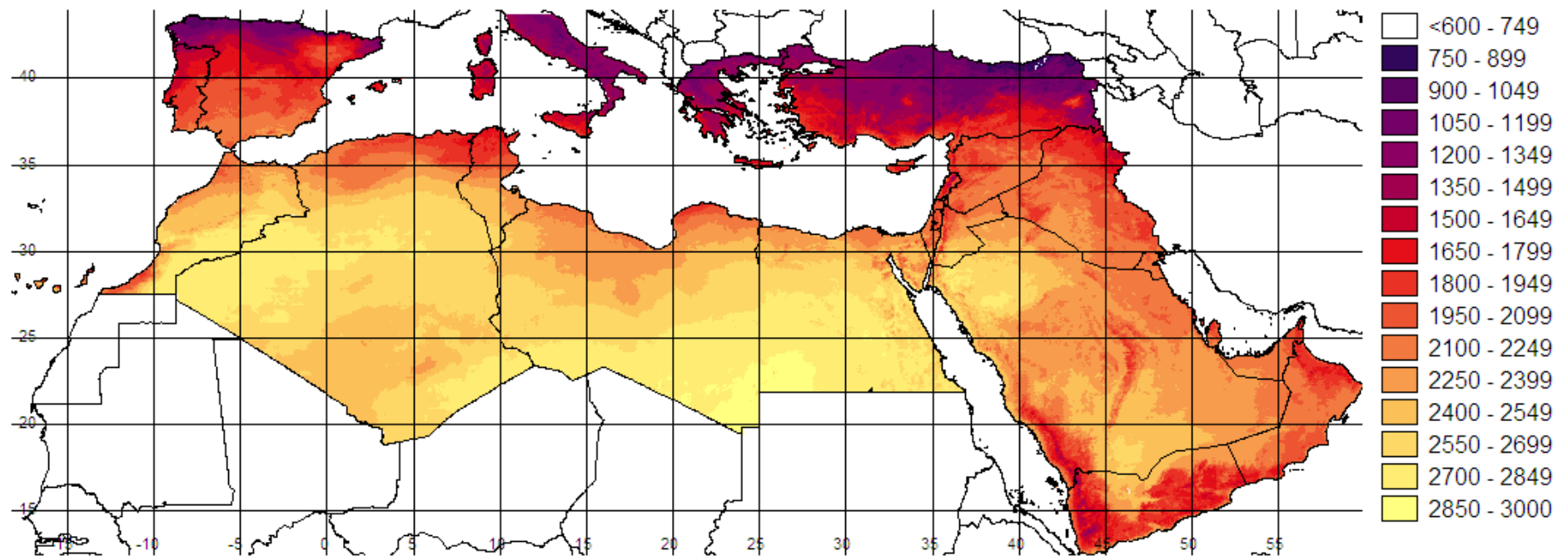


Solar Energy Resource Potentials

- Atlas of Annual Direct Normal Irradiance
- Atlas of Exclusion Areas
- Atlas of Natural Gas Pipelines
- Overlay and Statistical Analysis



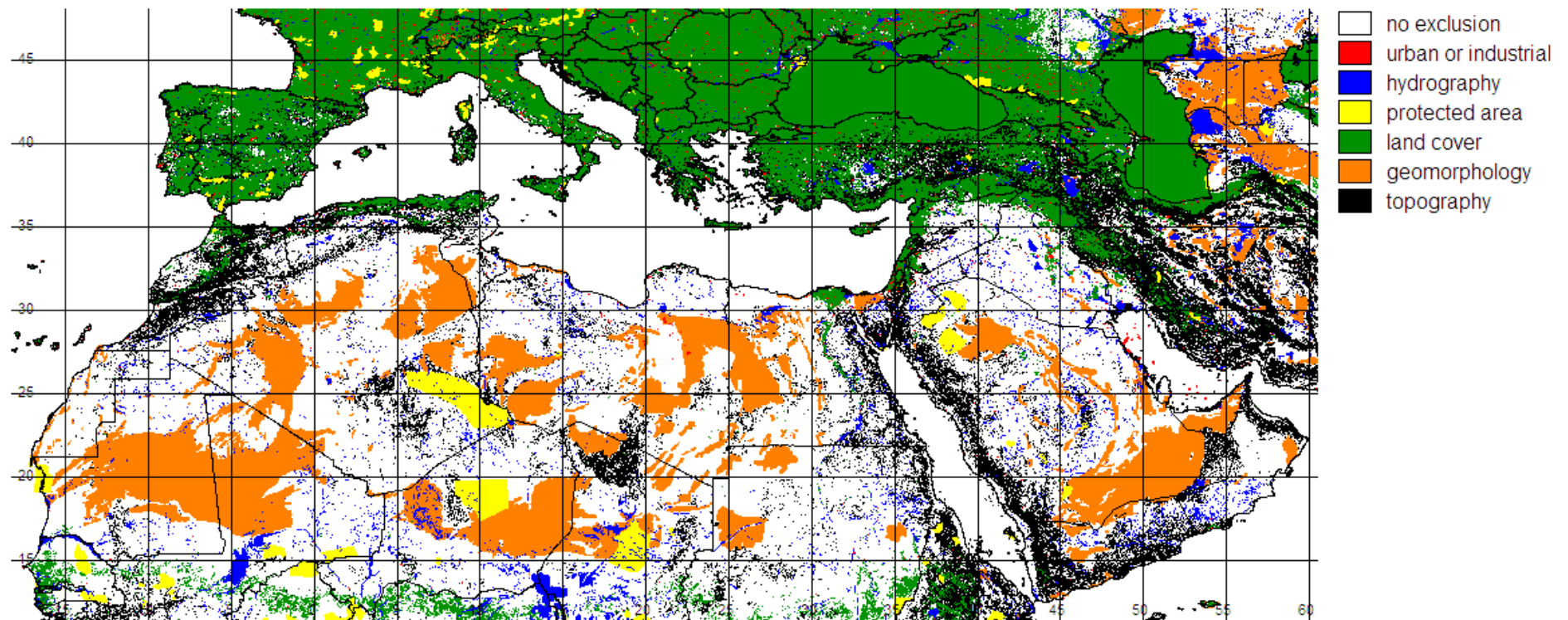
Atlas of Annual Direct Normal Irradiance



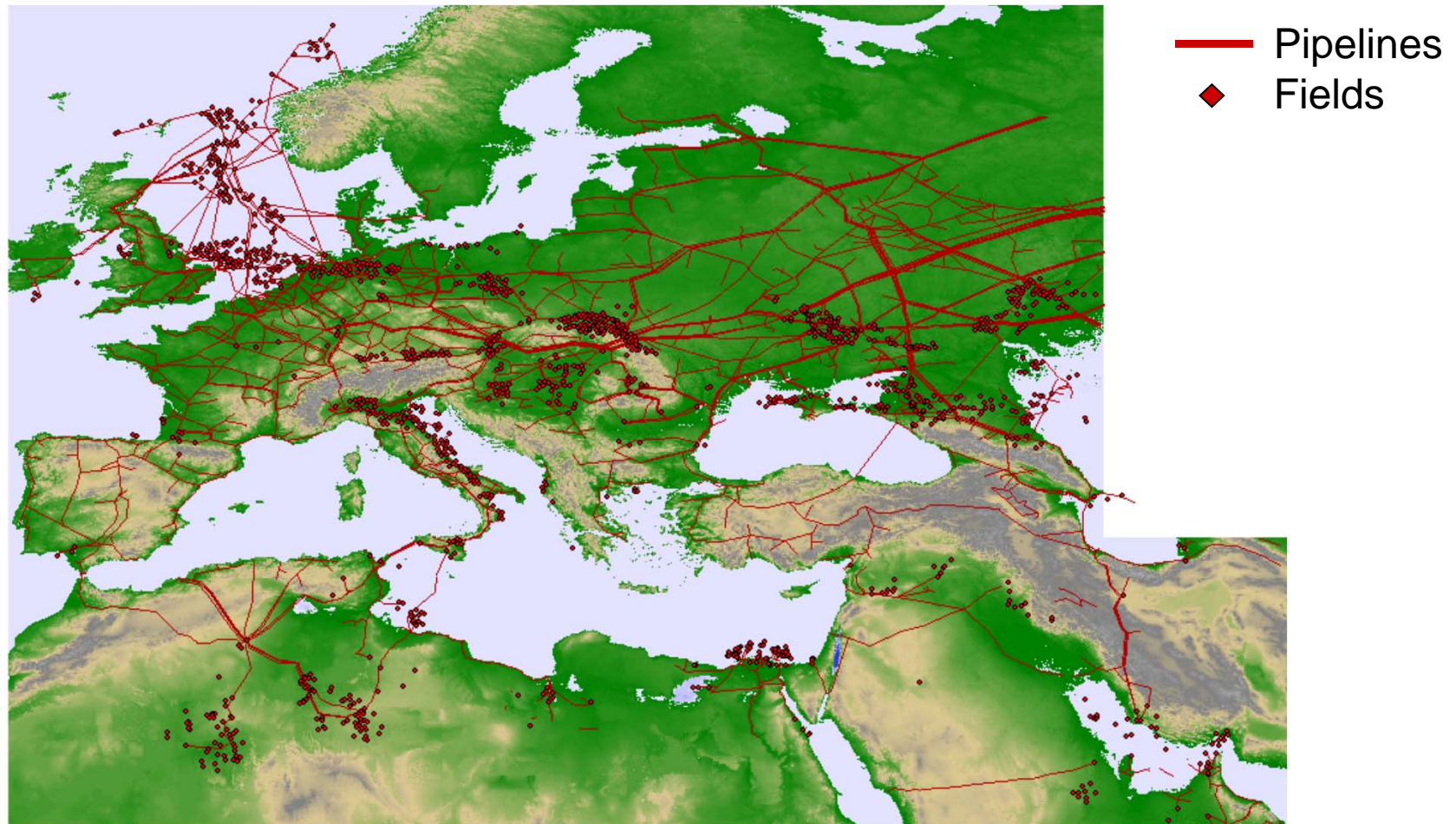
DNI 2002 in kWh/m²/y



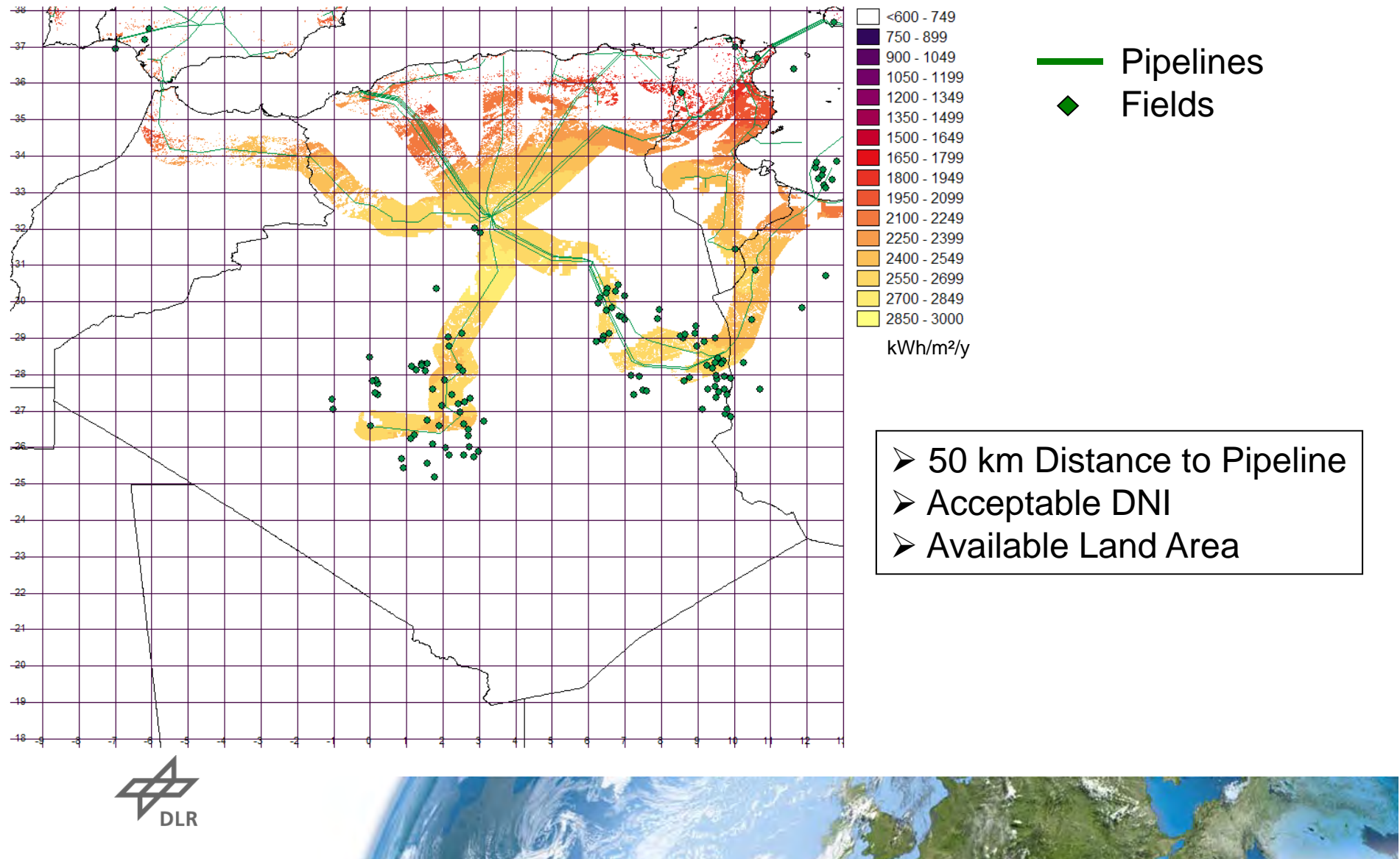
Atlas of Exclusion Areas



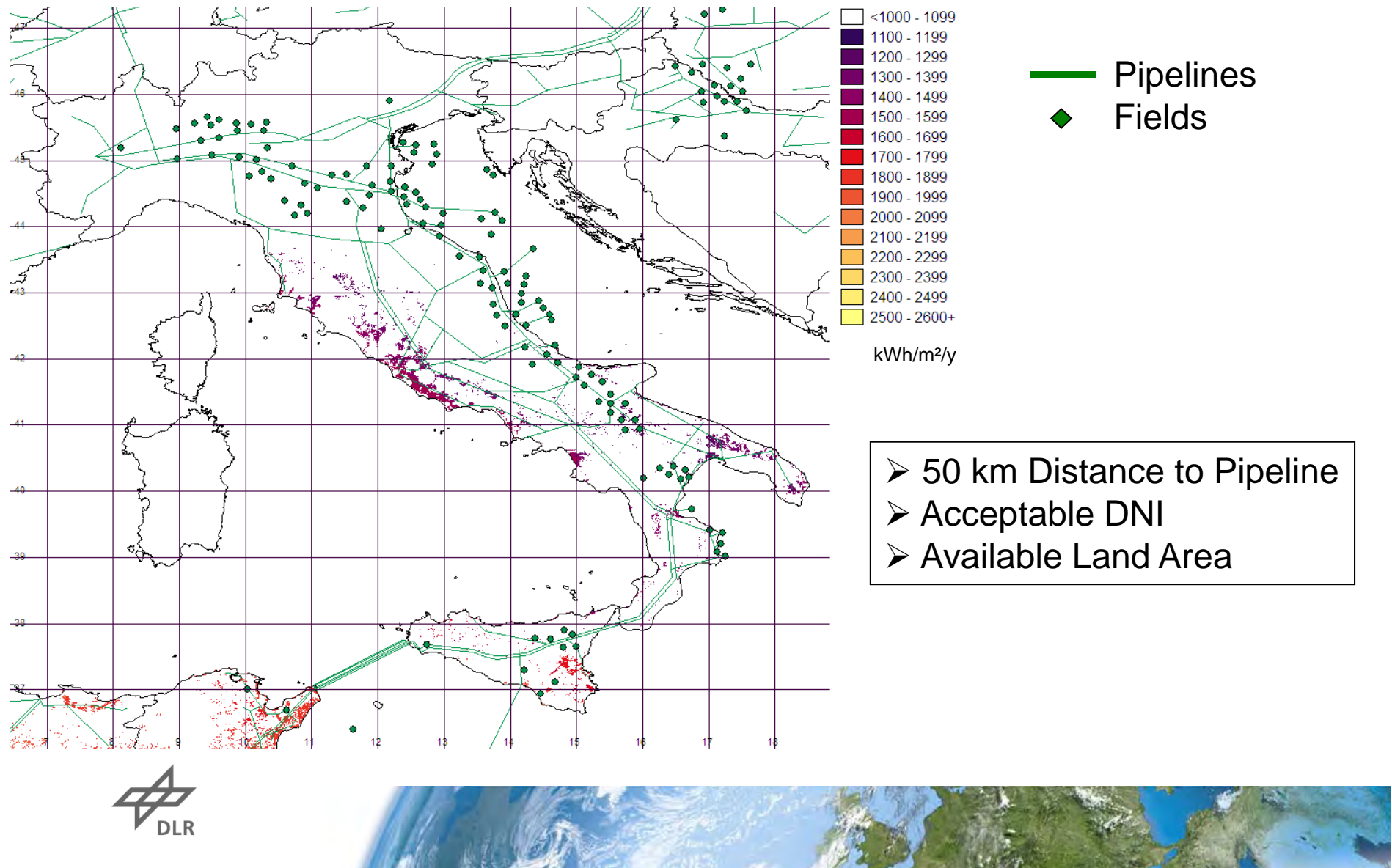
Atlas of Natural Gas Pipelines and Gas Fields



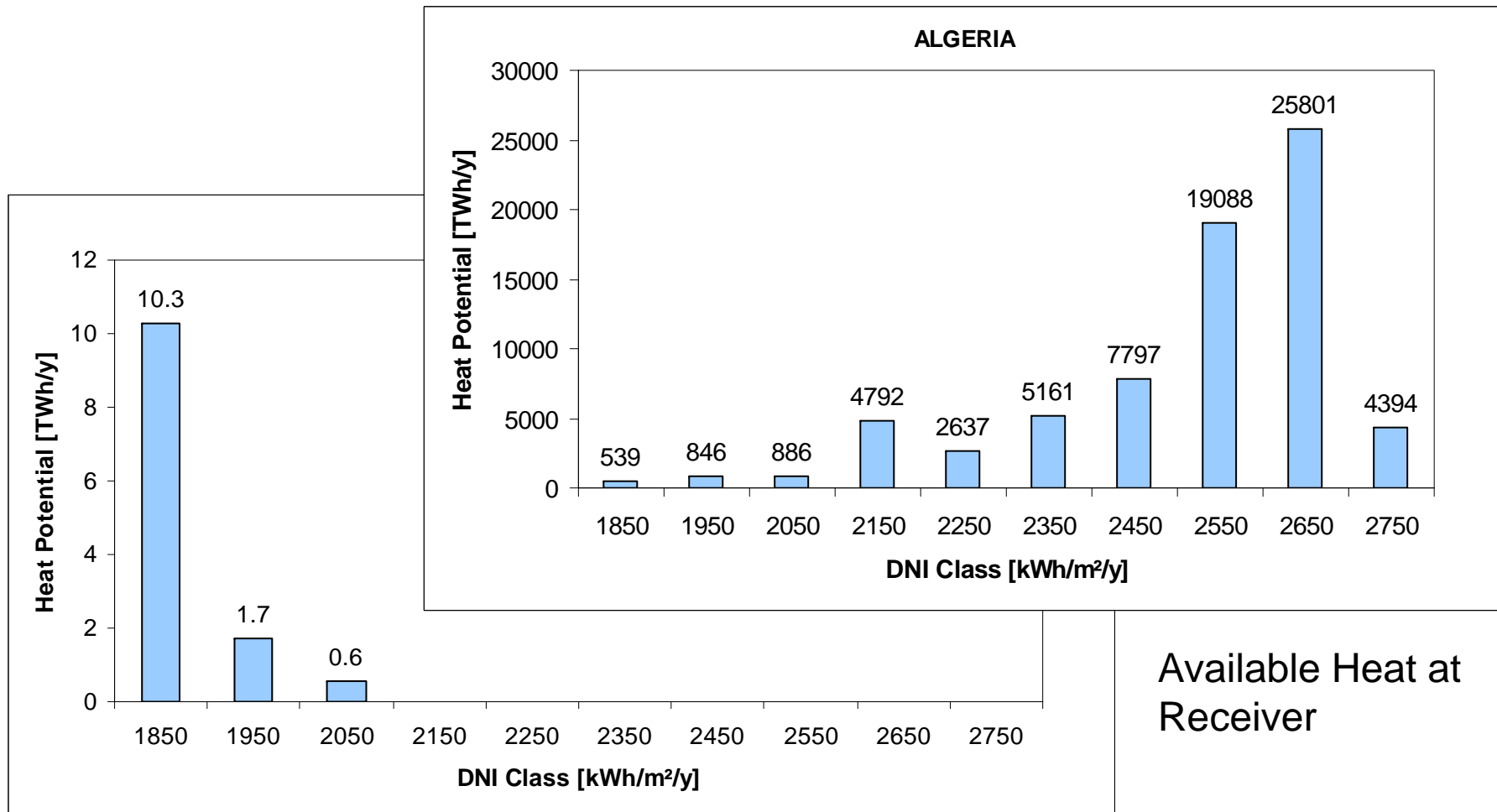
Overlay of Data Sets for Algeria



Overlay of Data Sets for Italy



Statistical Analysis



Market Scenario

- Overlay of Natural Gas and Solar Energy Potentials
- Scenario Analysis for Exporting and Importing Countries
- SOLREF Market Potential until 2050

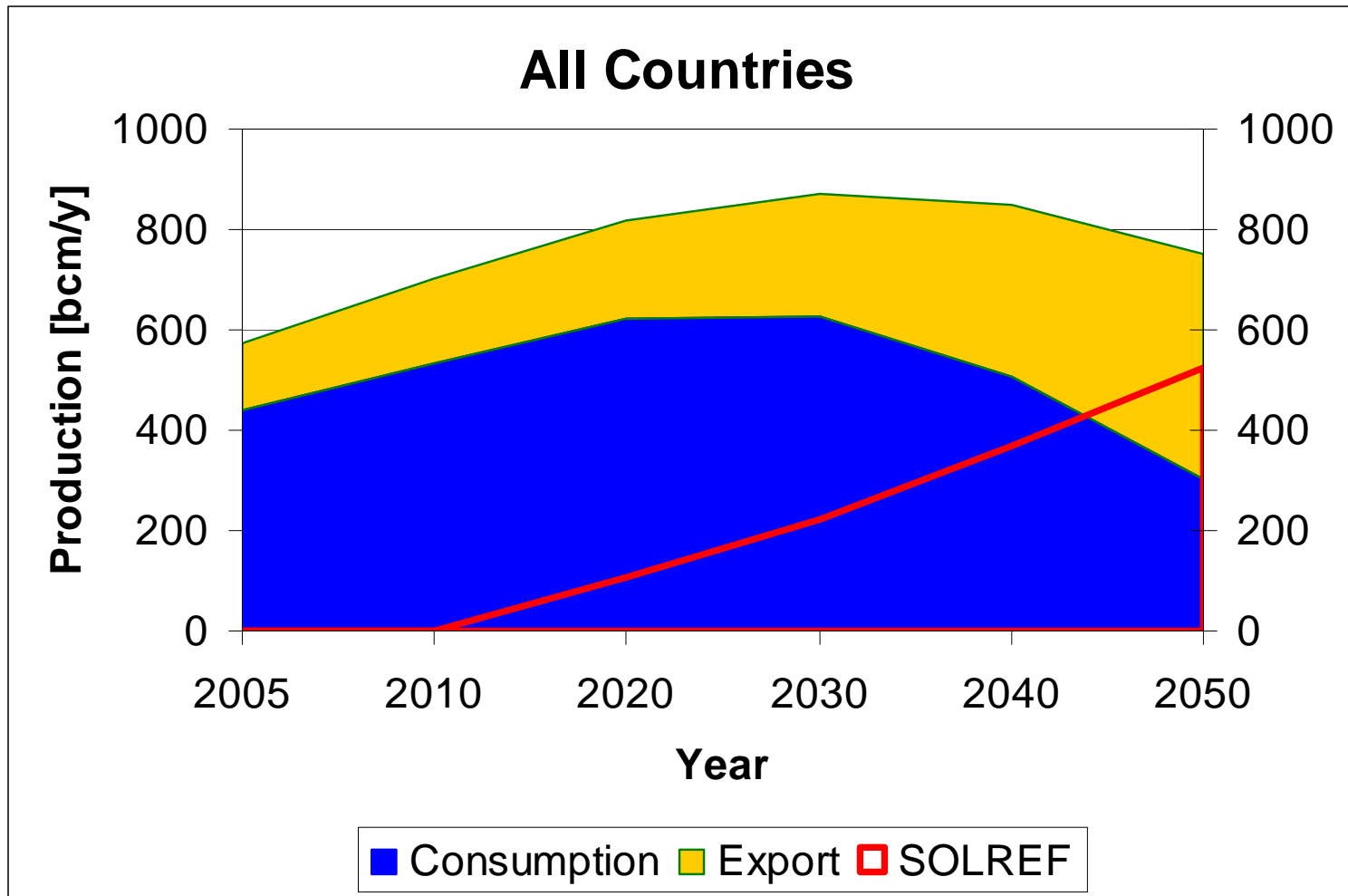


Overlay of Natural Gas and Solar Energy Potentials

Country	Technical SCCS Potential billion m³/y	Natural Gas Consumption 2005 billion m³/y	Natural Gas Export 2005 billion m³/y	Natural Gas Import 2005 billion m³/y	Proved Reserves 2005 billion m³	R/P Ratio 2005 years
North Africa						
Morocco	971	0.1	0.0	0.0	2	33
Algeria	17639	21.8	65.5	0.0	4504	52
Tunisia	2891	4.1	0.0	1.7	75	18
Libya	7693	10.4	1.3	0.0	1491	132
Egypt	5590	23.4	19.1	0.0	2704	64
Middle East						
Jordan	1353	1.5	0.0	1.2	6	4
Lebanon	0	0.0	0.0	0.0	0.0	0
Israel	194	0.7	0.0	0.0	37	51
Syria	1948	8.5	0.0	0.0	240	28
Iraq	4766	2.5	0.0	0.0	3170	1268
Iran	n.a.	93.5	4.4	0.0	26740	273
Arabian Peninsula						
Saudi Arabia	4065	68.3	0.0	0.0	6570	96
United Arab Emirates	535	40.2	6.8	1.3	6071	129
Kuwait	118	12.6	0.1	0.0	1586	125
Oman	4369	6.3	10.4	0.0	829	50
Qatar	148	18.3	27.5	0.0	25633	560
Bahrain	0	10	0	0	88	9
Yemen	0	0	0	0	1	0
Europe						
Spain	246	30.5	0.0	30.7	2.4	16
Portugal	4	4.3	0.0	4.3	0	0
Italy	2	82.0	0.0	70.5	217	3
Greece	0	2.7	0.0	2.7	0.9	0
Turkey	1	26.0	0.0	26.0	8.0	0

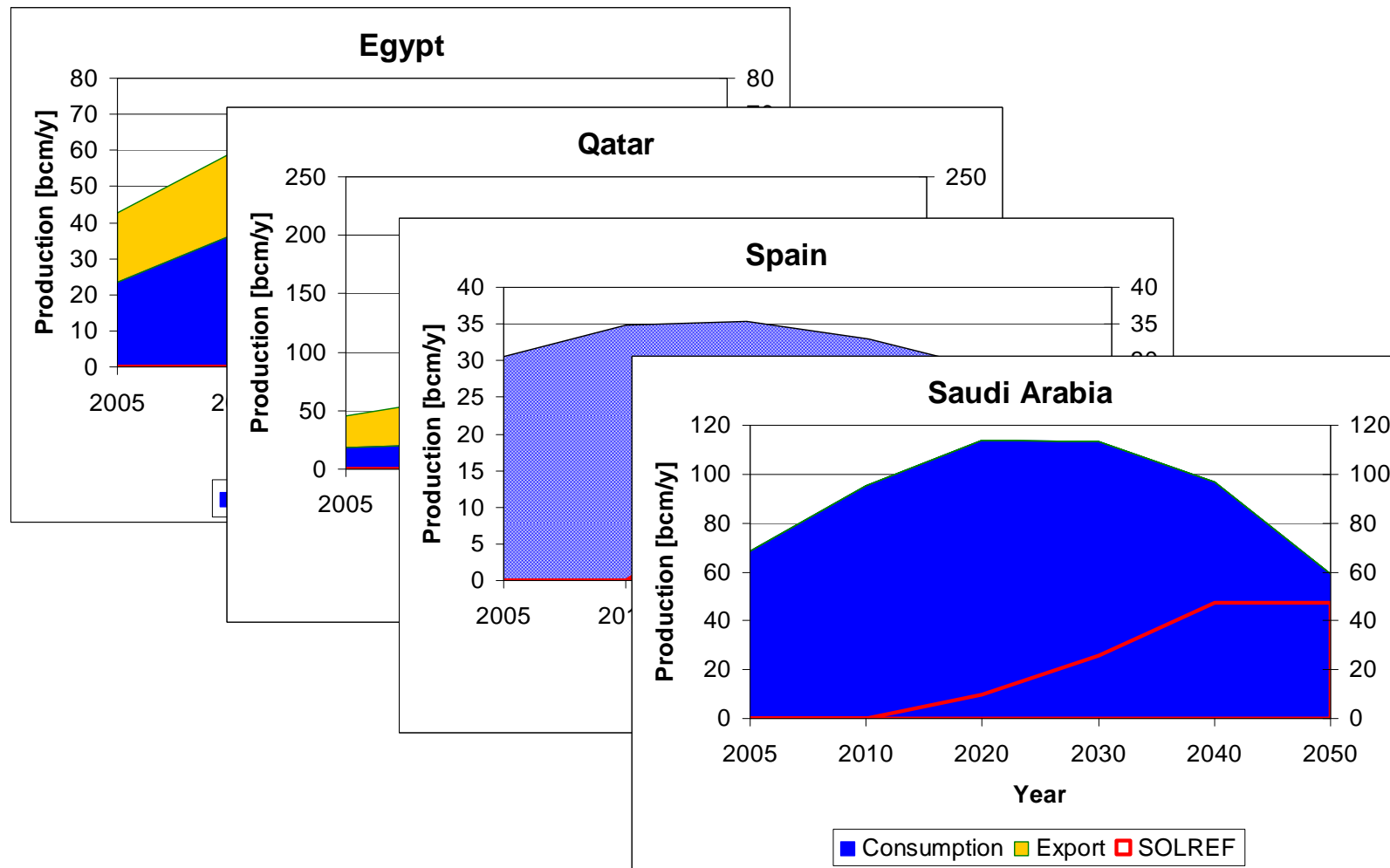


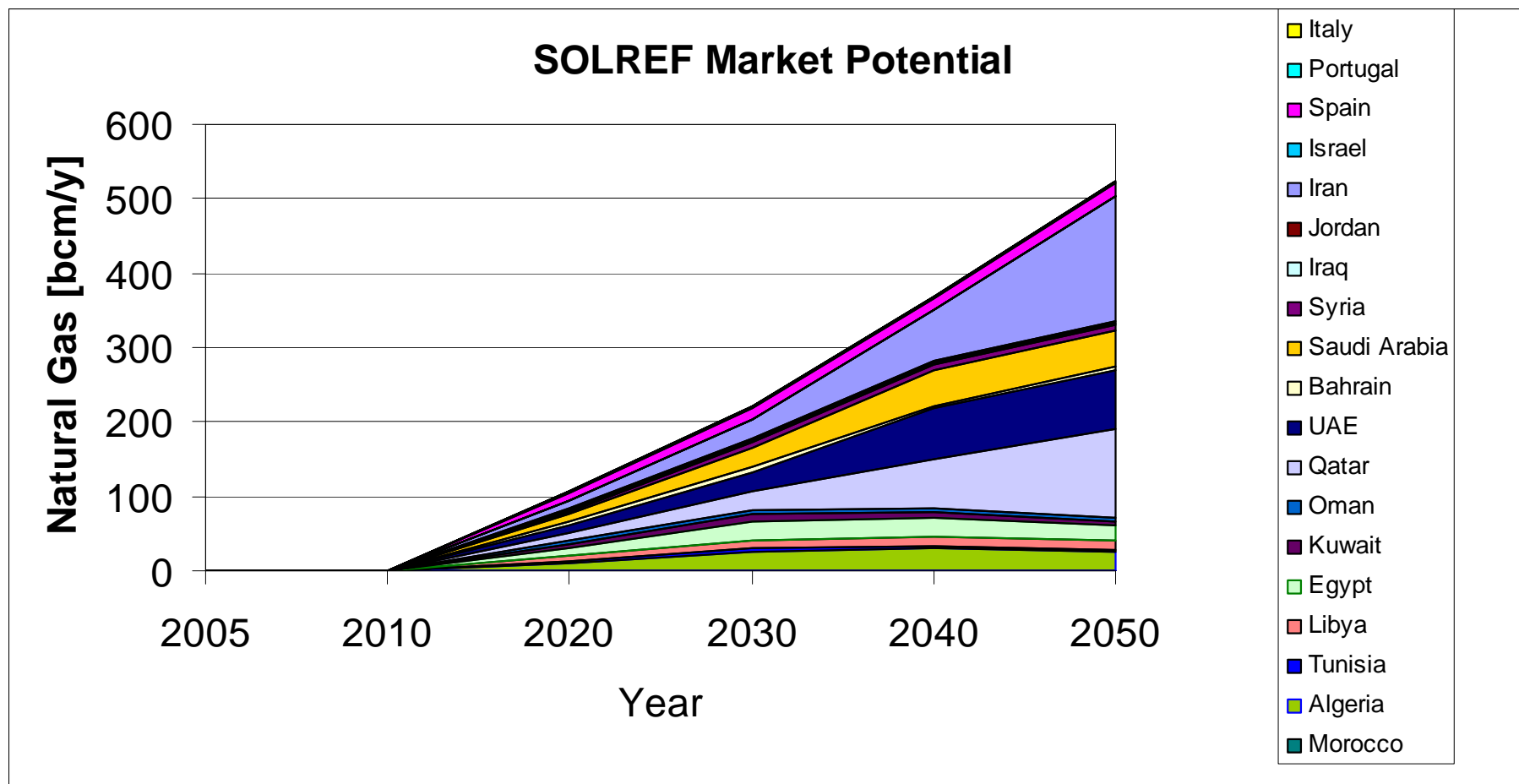
Natural Gas and SOLREF Markets

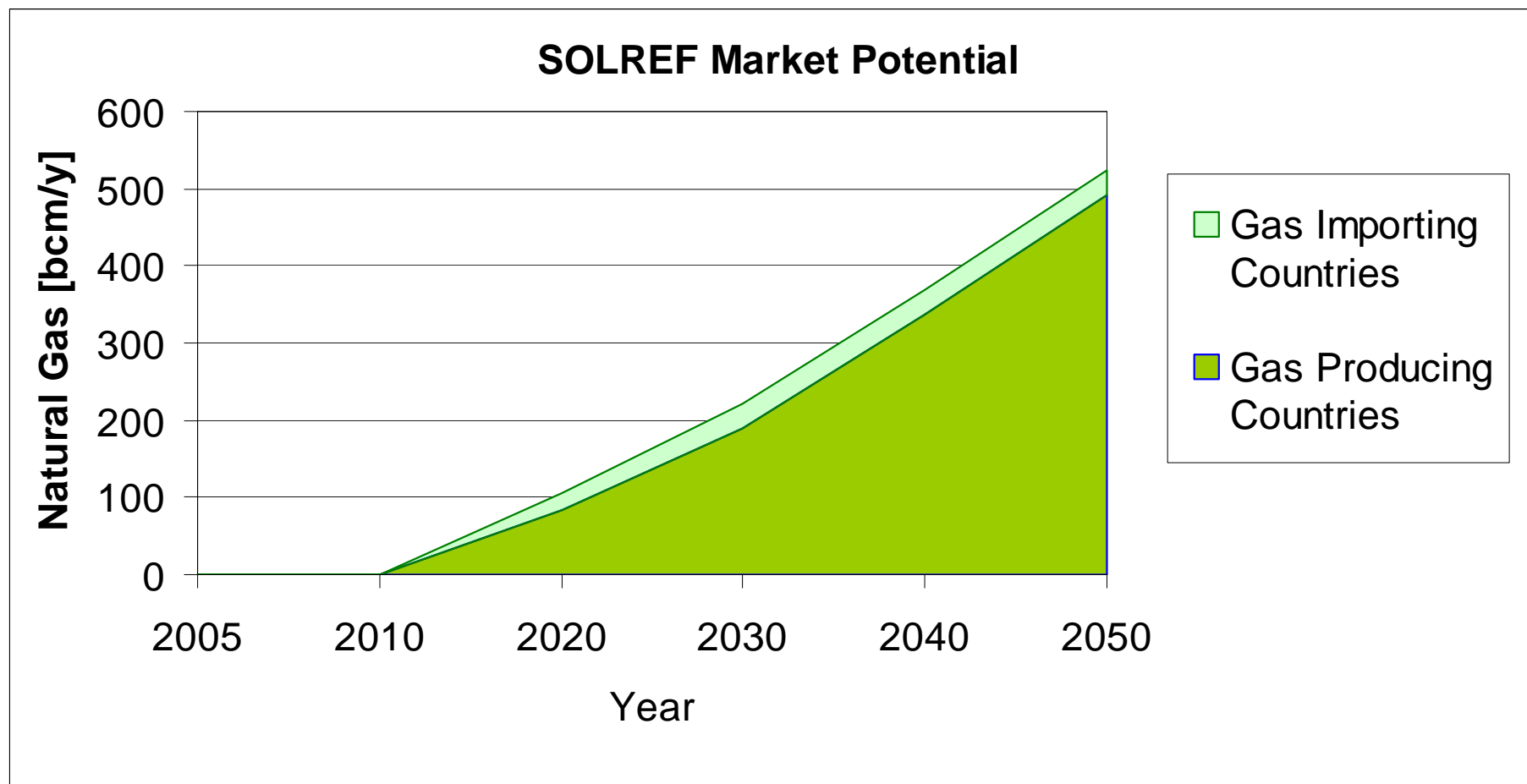


Production is consistent with MED-CSP and TRANS-CSP Scenarios







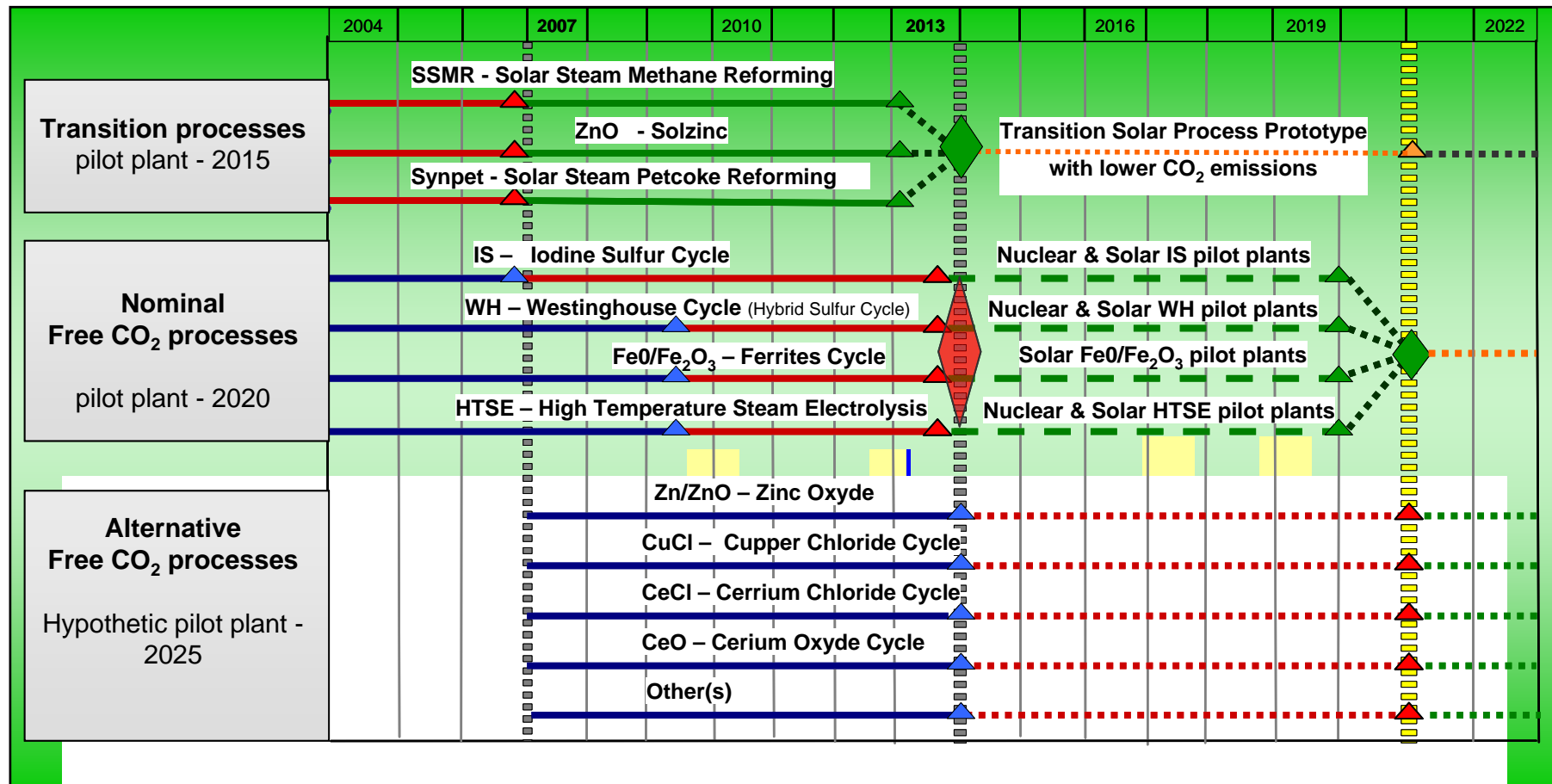


Environmental and Socio Economic Impacts

- Climate Change
- Land Use
- Energy Cost
- Energy Security and Availability
- Regional Cooperation



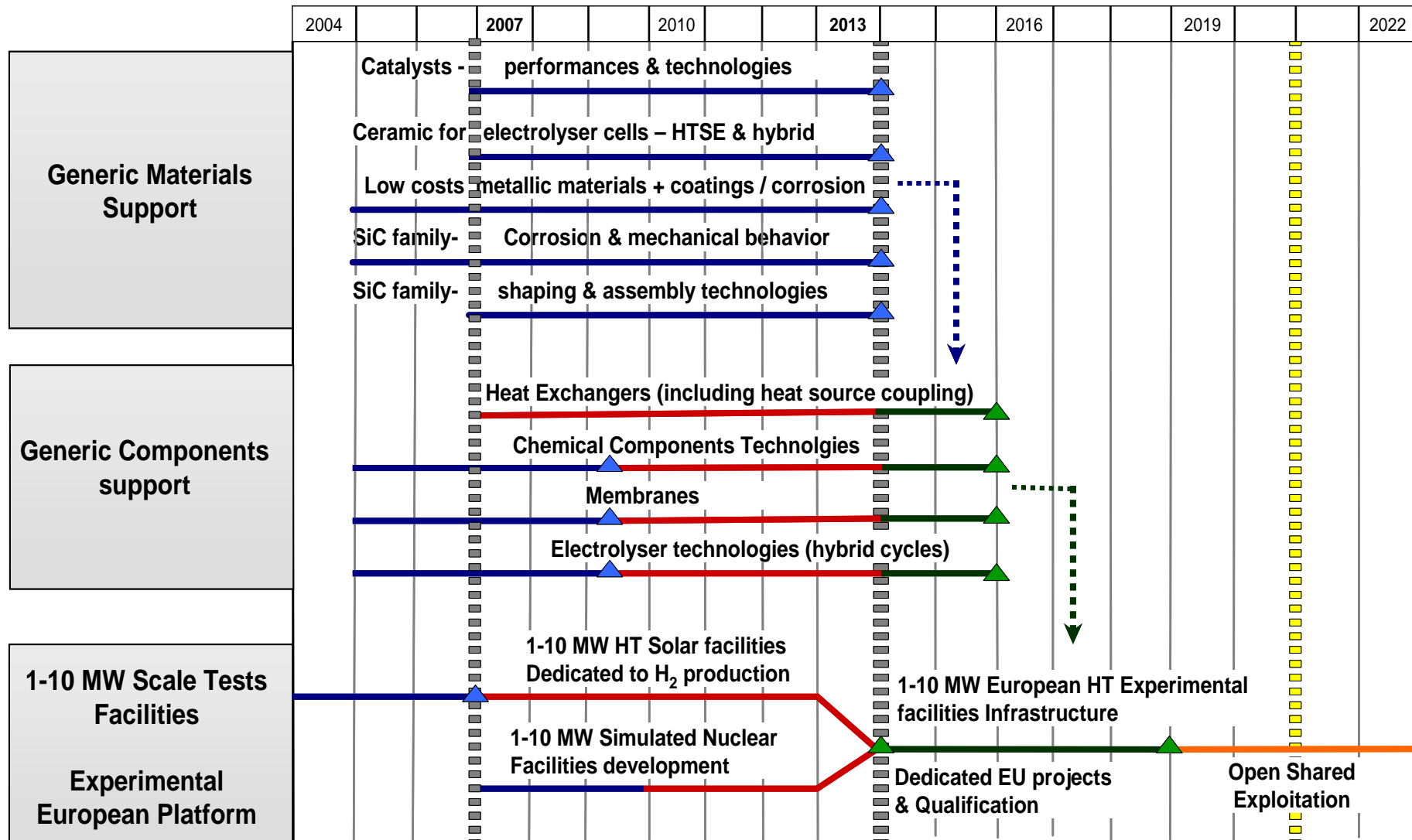
Massive High Temperature H₂ production Global R&D Roadmap



Three groups of processes depending on deployment maturity and market opportunities



The cross-cutting actions Roadmap



Acknowledgement

- Thanks to all our funding agencies especially the European Commission and our industrial partners.
- Thanks to all colleagues and partners who provided various contributions to this work.

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Thank you very much for your attention!

